

CRC REVIVALS

Soils in Waste Treatment and Utilization

Volume II: Pollutant Containment, Monitoring, and Closure

Wallace H. Fuller, Arthur W. Warrick



CRC Press
Taylor & Francis Group

Soils in Waste Treatment and Utilization

Volume II Pollutant Containment, Monitoring, and Closure

Authors

Wallace H. Fuller
Arthur W. Warrick

Department of Soils, Water and Engineering
University of Arizona
Tucson, Arizona



CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

First published 1985 by CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Reissued 2018 by CRC Press

© 1985 by CRC Press, Inc.
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Library of Congress Cataloging-in-Publication Data

Fuller, Wallace Hamilton.

Soils in waste treatment and utilization.

Bibliography: p

Includes indexes.

Contents: v. 1. Land treatment -- v. 2. Pollutant containment, monitoring, and closure.

1. Sewage disposal in the ground. 2. Land treatment of wastewater. 3. Soil pollution. 4. Soils.

I. Warrick, Arthur W. II. Title.

TD760.F85 1985 628.4'456 84-7047

ISBN 0-8493-5151-0 (v. 1)

ISBN 0-8493-5152-9 (v. 2)

A Library of Congress record exists under LC control number: 84007047

Publisher's Note

The publisher has gone to great lengths to ensure the quality of this reprint but points out that some imperfections in the original copies may be apparent.

Disclaimer

The publisher has made every effort to trace copyright holders and welcomes correspondence from those they have been unable to contact.

ISBN 13: 978-1-315-89762-2 (hbk)

ISBN 13: 978-1-351-07672-2 (ebk)

Visit the Taylor & Francis Web site at <http://www.taylorandfrancis.com> and the
CRC Press Web site at <http://www.crcpress.com>

PREFACE

Soils reflect their environment and, therefore, differ just as plants and animals do. They have easily recognizable characteristics which are used for classification. Their individual properties are acquired from the many forces acting upon them. These forces may be grouped into soil forming factors of, climate, biological systems, topography, parent material (mineral matter), and time. Thus, soils from one distinct climatic and geologic region differ from those of other regions. This book relates the different soil properties to their capacity to control movement of waste pollutants through them such as might be envisioned in a huge chromatographic column. It is these differences that makes it so essential to understand the reactions and interactions between soils and wastes as an essential function in soil management for waste control.

In these books, we bring together and correlate recent information known to have a prominent influence on the rate of movement of pollutants from wastes and their leachates in the soil. The emphasis is on those characteristics most amenable to modification and their management, such that secure and rational choices of disposal can be made. Identification of limits of the state of the art are carefully defined.

This book presents five distinct but related subject matter sections. The first topic relates to soil as a natural system to prepare the reader with a basic knowledge of soil properties as they must become involved in waste management at the disposal facility. The soil, its depth-profile, and certain characteristics are identified and described.

Historically, soils have demonstrated their function as waste utilization (resource) systems. In fact, soil organic matter originates from natural plant and animal residues that annually reach the soil surface and become incorporated. The farmer and home gardener have long extended waste utilization through application to the land of animal manure, green manure, composts, and other residues by use of simple as well as sophisticated techniques. Certain wastes, therefore, have been considered resources to be husbanded for improvement of soil productivity. In the second topic, we look at opportunities to manage industrial wastes as resources. Discussion of wastes as a resource is separated into two chapters based on use on cultivated and noncultivated land.

The third topic deals with those wastes that, at the present time, must be disposed of without immediate obvious benefit. The topics include such disposal options as land treatment, landfills, trenches, encapsulations, and other burials. Soil as lining material for landfills, impoundments, and ponds is included to describe the function of soil as an attenuation, absorption, and filter barrier for pollutants. Soil may be used as an effective medium for management of gases, odors, and aerosols as well as for solids and liquids.

Soils can retain pollutants either by ponding the liquid at the surface through infinitely slow permeability or by attenuation of pollutants leaching from hazardous waste while allowing acceptable leakage of potable quality water to reach groundwater. Furthermore, soils can biodegrade organic-containing wastes to harmless constituents. The fourth topic therefore, presents descriptions of research methods used for predicting both biodegradation and mobility of pollutants through soils as affected by specific soil and leachate properties. Progress on screening protocol for predicting waste treatability, models for predicting metal pollutant movement through soil, and effects of hydrogen ion concentration of acid wastes on pollutant retention and soil failure are discussed. Again, unfavorable as well as favorable situations are identified.

The final subject relates to site selection for waste disposal, monitoring, site-facility closure and continued surveillance. Predisposal, disposal, and postdisposal monitoring are considered.

Because soil management for pollution waste control is a new and unusually broad subject to encompass under the cover of one book, the level of presentation and consequent comprehension is not established at a constant level as we would like. Available literature and

data are scattered, fragmentary, and often conflicting. Consequently, for some topics the emphasis is as a review, in others more as a statement of fact, and in still others almost as a journal paper or research report. Despite these circumstances, we hope to reach the main audience of concerned people who are responsible for planning, designing, managing and operating wastes and wastewater disposal facilities. In addition, educators and researchers probably can benefit.

There is no doubt that newer and more accurate information is developing in great abundance each year which will soon antedate this book and call for a revision. However, this work is presented as a framework for a realistic base of departure on which to hang new guidelines and new ventures in a rapidly advancing field of soils as waste treatment/resource utilization systems.

The Authors

THE AUTHORS

Wallace H. Fuller, Ph.D., is a professor and biochemist in the Department of Soils, Water and Engineering at The University of Arizona, Tucson, Arizona, where he teaches and is leader of the waste research program. He received the B.S. and M.S. degrees in Soil Science, Washington State University and Ph.D. in Soil Bacteriology and Biochemistry, Iowa State University. His early experience as soil surveyor in Wisconsin, Missouri, and Iowa and Research Associate at Washington State University as agrochemist, and Iowa State University as head of War Hemp Industry investigations provides a practical background for the long research tenure in land treatment of unwanted residues as resources, as well as waste requiring final and secure disposal. Early training (1945 to 1948) in atomic energy and radionuclide research in biophysical chemistry with the USDA, ARS, Agricultural Research Center, Beltsville, Maryland, equips him well for developing critical research and publications in waste control.

During Dr. Fuller's tenure as Head of Agricultural Chemistry and Soil Department at The University of Arizona (1956 to 1972), he continued research activities and published over 175 scientific journal papers, authored two books on arid land soils (*Soils of the Desert Southwest* and *Management of Southwest Desert Soils*), and wrote many chapters in books on waste management. Another book, *Scientific Management of Hazardous Wastes*, from Cambridge University Press (1983) is co-authored by Dr. Fuller with two British authors. He shared honors as Special Associate with Water Resource Associates, Inc., whose Greenbelt Flood Control Project was selected by the National Society of Professional Engineers as one of the top ten outstanding engineering achievements of 1974.

Dr. Fuller's experience in waste management includes 14 years on the Arizona State Water Quality Control Council; 16 years as State Chairman of the Advisory Committee to the Arizona State Chemist Office on agricultural chemicals, feeds, pesticides, and minerals; Consultant and Advisor to U.S. Department of Public Health (HEW) and U.S. EPA National Project Review Council (1960 to 1972); and Consultant to scientific enterprises in South America, Panama, and Mexico governments. He has been awarded many research grants, contracts, and cooperative projects from industry, the Atomic Energy Commission, the U.S. Department of Agriculture, U.S. Environmental Protection Agency, and private enterprises as principal investigator. He also is a noted national and international consultant on water quality, hazardous waste management, environmental quality control, and arid-land soils.

A. W. Warrick is Professor of Soil Physics at The University of Arizona in Tucson. He received a B.S. degree in Mathematics and a M.S. and Ph.D. (1967) in Soil Physics at Iowa State University. Research and teaching topics include flow through porous media along with associated transfer of solutes and materials. Emphasis is on theoretical description of these processes and modeling. Sampling and the quantification of spatial variability through geostatistics and other techniques are of particular current interest. He has been involved with several projects dealing with waste disposal; including septic tanks, radioactive wastes, solvents, and gaseous wastes.

Dr. Warrick has served as chairman of the S-1 Division of the Soil Science Society of America as well as an associate editor of the SSSA Journal. He has authored over 75 scientific journal papers or book chapters.

ACKNOWLEDGMENT

We are deeply indebted to many individuals and organizations for the use of material. We especially thank those who provided soils from throughout the United States to make much of the research discussed here possible:

Drs. S. W. Buol, North Carolina State University; L. R. Follmer, University of Illinois; R. E. Green, University of Hawaii; D. M. Hendricks, University of Arizona; M. R. Roulter, U.S. E.P.A.; E. P. Whiteside, Michigan State University; and A. L. Zachary, Purdue University.

We are especially grateful to the U.S. Environmental Protection Agency and project officers: M. H. Roulter of MERL in Cincinnati, Ohio, who contributed time and encouragement for the heavy metal attenuation and model development and L. G. Swaby, ORD U.S. EPA, Washington, D.C., who as project officer, contributed to the successful completion of the research on hydrogen ion effects in soils presented in Chapter 6, Volume II. Special appreciation goes to the University of Arizona staff who were involved in the waste control research, as related to groundwater quality and food chain protection, included in this book, foremost of whom are: N. E. Korte; E. E. Niebla; B. A. Alesii; J. F. Artiola; J. Skopp; Ronda Bitterli; and P. J. Sheets. Aziz Amoozegar-Fard deserves special recognition and thanks for his long devotion to soil-waste interaction research and mathematical model computations.

Foremost in support of these volumes is the patience and understanding of Winifred Fuller who deserves more than can be put into words.

We appreciate the opportunity the University of Arizona College of Agriculture and Department of Soils, Water and Engineering provided for the completion of this research program and manuscript preparation. Significant encouragement was provided by our department head, W. R. Gardner.

Long hours of work in the preparation of the manuscript were generously supplied by Mary Schreiner in text review; by Susan Angelon, who devoted unlimited time and talent to the art preparation, graphs, and photographs; by Olivia Ayala, typist; by Sheri Musil with the final manuscript review; and by Lisa Littler, Coordinating Editor.

Wallace H. Fuller
Arthur W. Warrick

TABLE OF CONTENTS

Volume I

Land Treatment

SOIL AS A NATURAL SYSTEM

Chapter 1

The Soil, Profile and Characteristics	3
I. The Soil	3
A. Description	3
B. Three-Phase Soil System	3
1. The Solid Phase	4
a. Soil Organic Matter	4
b. Total Element Analyses	4
c. The Lithosphere	5
d. Primary Silicate Minerals	5
e. Aluminosilicates	8
f. Representative Referee Soils	9
2. The Liquid Phase	11
3. The Gaseous Phase	14
C. The Soil Profile	14
D. The Soil Classification	17
II. Biological Characteristics	21
A. The Microflora	21
B. Biodegradation	24
1. Important Biological Processes	24
2. Temperature	24
3. Moisture	26
4. Oxygen Status	27
5. Acidity and Alkalinity (pH)	27
6. Carbon/Nitrogen Ratio	27
C. Oxidation/Reduction	28
D. Mineralization and Immobilization	29
1. Complexation with Organic Constituents	31
2. Cometabolism	33
3. Recalcitrant Molecules	35
III. Chemical Characteristics	36
A. Chemical Properties	36
B. Chemical Equilibria	37
C. Ion Exchange	37
D. Transfer of Protons and/or Electrons	41
E. Soil pH (Acidity and Alkalinity)	43
IV. Physical Characteristics	45
A. Physical Properties	45
B. Particle Size and Surface Area	45
C. Soil Structure	48
D. Kind of Clay Material	50

E.	Pore Size Distribution and Porosity	50
1.	Total Porosity	50
2.	Bulk Density	51
3.	Particle Density	51
4.	Pore Size Distribution	51
5.	Compaction	54
6.	Cementation	54
7.	Stratification	54
F.	Hydration and Dehydration	56
V.	Soil Water	57
A.	Water Content	57
B.	Soil Water Potential	59
1.	Measuring Gravitational Potential	60
2.	Measuring Pressure Head — Saturated Conditions and Positive Pressures	60
3.	Measuring Pressure Head — Unsaturated Conditions, Low Suctions	60
4.	Measuring Pressure Head — Drier Conditions	61
5.	Notations and Alternative Expressions of Soil Water Potential	63
C.	Soil Water Dynamics	64
1.	Saturated Flow	65
2.	Measuring Hydraulic Conductivity — Saturated Flow	66
3.	Unsaturated Flow	68
4.	Convective Velocity	68
	References	70

SOIL AS A WASTE UTILIZATION SYSTEM

Chapter 2

Waste Utilization on Cultivated Land

I.	Rationale and Scope	77
II.	Waste Resources for Cultivated Land	79
III.	Soil Management of Solid Wastes	80
A.	Procedure for Land Utilization of Wastes	82
B.	Placement of Solid Waste	83
1.	Surface Placement	83
2.	Soil Incorporation	86
C.	Solid Waste Loading Rates	87
1.	Animal Manures and Municipal Sludges	87
2.	Municipal Solid Waste	89
3.	Compost	90
4.	Oily Wastes	93
5.	Paper Pulp Mill Waste	94
6.	Wood and Forest Waste	94
7.	Cannery Wastes	96
8.	Industrial Processing Wastes	96

	9. Soil Amendments	96
IV.	Soil Management of Liquid Wastes	104
	A. Application Mode for Wastewaters on Cultivated Land	105
	1. Surface Application (Methods)	105
	2. Soil Incorporation	111
	B. Wastewater Loading Rates	113
	1. Criteria Determining Wastewater Loading	114
	2. Wastewater Quality and Loading Rates	116
	3. Soil Properties and Loading Rates	125
	4. Climatic Characteristics and Loading Rates	134
	5. Time and Loading Rates	136

References	137
------------------	-----

Chapter 3

Waste Utilization on Noncultivated Land	141
I. Rationale and Scope	141
A. Advantages and Disadvantages	141
B. Kinds of Wastes Adapted to Uncultivated Land	142
C. Land Types Most Suited	143
II. Soil Management of Solid Wastes	144
A. Methods of Application	144
B. Placement or Design	145
C. Solid Waste Loading Rates	145
1. Shredded Municipal Solid Waste	148
2. Sewage Sludge and Septic Tank Waste	148
3. Compost	151
4. Wood and Paper Mill Wastes	151
5. Tannery Wastes	152
6. Cannery Wastes	154
7. Acid Wastes	154
8. Oils and Oily Wastes	154
9. Flue-Gas Cleaning Wastes	157
10. Others	159
III. Soil Management of Wastewaters	160
A. Methods of Application	161
1. Spray Irrigation	161
2. Ridge and Furrow and Flood Systems	163
3. Overland Flow	164
4. Rapid Infiltration	166
5. Subsurface Injection	170
6. Wetlands Application	170
B. Disturbed Lands	173
1. Strip-Mine Spoil	174
2. Iron-Mined Lands	176
3. Spent Oil Shale	176
4. Overburden, Tailings, Sand Dunes, and Playa	177
5. Saline and Alkali Waste Lands	178
6. Urban Lands	181

C.	Wastewater Loading Rates	181
1.	Nitrogen	182
2.	Phosphorus.....	183
3.	Organic Matter (BOD, COD, TOC)	184
4.	Heavy Metals	184
5.	Organic Toxicants	186
6.	Human Pathogens	186
IV.	Effect on Ecosystems	186
	References.....	187

SOIL AS A WASTE TREATMENT SYSTEM

Chapter 4

	Waste Treatment on Land Primarily for Disposal	195
I.	Scope	195
II.	Historical Introduction	195
III.	Land Treatment Practices	198
A.	Constraints	198
B.	Solid Wastes	200
1.	Municipal Solid Wastes.....	200
2.	Refractory Metal Processing Waste	200
3.	Petroleum Refining Waste	201
4.	Leather Tanning and Finishing.....	202
5.	Pulp and Paper Industry Waste	203
6.	Textile Industry Waste	204
7.	Specific Acids	204
C.	Liquid Wastes	206
1.	Pesticides	206
2.	Pharmaceuticals, Cosmetics, Soaps, and Detergents	207
3.	Wastes Related to Agricultural and Forestry Industries	209
IV.	Waste Characteristics and Loading Rates	210
A.	Waste Factors Effecting Loading Rates.....	210
B.	Loading Rate Limitations.....	213
1.	Hydrological Balance	213
2.	Plant Nutrients	213
3.	Salt and Sodium	216
4.	Metals	216
5.	BOD and TOC.....	217
6.	Toxic Organics	221
V.	Soil Management	221
A.	Predisposal Land Preparation.....	222
B.	Soil Erosion Control.....	223
1.	Erosion by Water	226
2.	Erosion by Wind.....	229

C.	Water Control	231
1.	Runoff	231
2.	Rainfall	237
3.	Watershed	241
4.	Water Modification Practices	241
5.	Water Control Practices.....	242
	References.....	245

APPENDIXES

USDA and USCS Particle Classifications	251
English-SI Conversion Constants	254
Abbreviations, Signs, and Symbols	255

INDEX.....	261
------------	-----

Volume II

Pollutant Containment, Monitoring, and Closure

SOILS INVOLVED WITH WASTE BURIALS

Chapter 1

Landfills, Trenches, Encapsulations, and Other Burials	3
I. Rationale and Scope	3
II. Sanitary Landfill	3
A. Scope.....	3
B. Development	4
C. Limitations	5
D. Site Selection.....	5
E. The Soil	9
1. Landfill Liners	13
2. Landfill Covers	16
3. Revegetation	20
III. Trenches	21
IV. Encapsulation	25
References.....	25

Chapter 2

Soil Liners for Landfills, Impoundments, and Ponds	27
I. Rationale and Scope	27
II. Soil Properties Affecting Attenuation	28

III.	Liners	30
A.	Concepts of Liners	30
B.	Compacted Soil	31
C.	Salt-Expanded Soil	33
D.	Soil Cements	33
E.	Soil Sealants	33
F.	Limestone Liners	36
1.	Crushed Limestone	36
2.	Leachate Relationships.....	39
3.	Limestone Particle Size	40
4.	Limestone Quality	40
5.	Limestone Thickness.....	41
G.	Hydrous Oxides of Iron	41
IV.	Liners for Burials	42
A.	Landfills.....	42
1.	Attenuation of Pollutants.....	42
2.	Waste Characteristics	44
3.	MSW Leachate Effects upon Liners	44
4.	Kinds of Soil Liners for Landfills.....	50
B.	Trenches and Encapsulations	50
V.	Liners for Surface Impoundments.....	50
VI.	Liners for Freshwater Ponds	52
A.	Freshwater Ponds.....	52
B.	Oxidative Ponds.....	52
C.	Sediment Collection Ponds	53
D.	Embankment Ponds	53
E.	Excavated Ponds	54
F.	Aquaculture Ponds	54
	References.....	55

Chapter 3

	Gases, Odors, and Aerosols	59
I.	Scope	59
II.	Gas Control.....	59
A.	Origin and Nature of Waste Gases	59
B.	Gas Movement through Soil.....	61
C.	Gas Control	63
1.	Reduction in Production	63
2.	Channels, Vents, Piping, Cover Control, and Barriers.....	64
3.	Collection and Absorption of Gases.....	64
4.	Chemical Combinations.....	66
D.	Gas Monitoring.....	66
III.	Odor Control.....	67
A.	Origin and Nature	67
B.	Odor Detection and Movement.....	67
C.	Odor Control	68
D.	Odor Monitoring	68

IV.	Aerosols	68
A.	Microbial Aerosols	68
B.	Dust and Other Emissions	69
V.	Soil Filter-Scrubbers	69
A.	Application	69
B.	General Principles and Procedures for Use	70
C.	Biochemical and Biological Aspects	71
D.	Physical Aspects	72
	References	73

PREDICTING POLLUTION TRANSFORMATIONS AND MOBILITY

Chapter 4

	Screening Protocol for Predicting Waste Treatability	77
I.	Scope	77
A.	Disposal Controls	77
B.	Purpose	77
C.	Generating Data for Predictions	78
D.	Previous Work	78
II.	Screening Tests and Pilot Experiments	80
A.	Requirements of the Test	80
B.	Controlled Laboratory Tests vs. Natural Field Tests	80
III.	Specific Methods	81
A.	Soil Sampling	81
B.	Chemical Analyses	85
C.	Physical Analyses	86
D.	Microbial Population and Biodegradation	86
	1. Dilution Plating Technique	87
	2. Respirometry	88
E.	Acute Microbial Toxicity and Biodegradation	89
	1. Toxicity Reduction via Microtox™ Analyzer	89
	2. Field Plot Toxicity Reduction Experiments	90
	3. Dehydrogenase Activity Method	90
F.	Chronic Microbial Toxicity and Mutagenicity	91
G.	Phytotoxicity	91
	1. Seed Germination Method	91
	2. Seedling Establishment Method	92
	3. Root Mat Technique	93
H.	Mineral Excess and Plant Growth Decrement	93
	1. Controlled-Environment Plot Experiments	93
	2. Field-Plot Experiments	94
I.	Permeability	95
J.	Volatilization	95
K.	Soil Erosion	96
	1. Soil Loss Equation	96
	2. Wind Erosion Equations	96
	3. Water Runoff	97

L.	Attenuation	98
1.	Batch Studies	98
2.	Soil Thin-Layer Chromatography	99
3.	Lysimeters	99
IV.	The Soil-Column Technique	99
A.	Approach	99
B.	Techniques Associated with the Soil	100
1.	Soil Selection	101
2.	Preparing the Soil for the Column	101
3.	Packing the Soil in the Column	101
C.	The Transport Vehicle — Four Major Categories	103
1.	Dilute Aqueous Inorganic and Aqueous Inorganic/Organic Fluids — Category A	104
2.	Aqueous Organic Fluids — Category B	104
3.	Strong Aqueous Acids, Bases, and Oxidizing Agents — Category C	105
4.	Organic Solvents — Category D	106
D.	Equipment Used for the Actual Tests	106
1.	Kinds of Soil Columns	106
2.	The Complete Soil-Column System	107
E.	Application of Influent to Soil Column	109
1.	Anaerobic (Anoxic)	109
2.	Aerobic (Oxic)	109
F.	Collection of Effluent from Soil Column	110
G.	Collecting and Processing Data	110
1.	Soils Data	111
2.	Transport Fluid Data	111
3.	Soil-Column Data	112
4.	Breakthrough Curves and Statistical Analysis	112
H.	Predicting Pollutant Movement	112
1.	Direct Application of Breakthrough Data	113
2.	Development of Models for Prediction	116
I.	Advantages and Limitations	118
1.	Limitations	118
2.	Advantages	118
	References	119

Chapter 5

	Models for Predicting Pollutant Movement through Soil	123
I.	Approach	123
II.	Predictions Using Soil Column Data	124
A.	Ranking of Pollutants According to Soil Interactions	124
B.	Predictions Using Soil and Pollutant Breakthrough Curves	124
C.	Predictions Using Soil Column Data with Mathematical Models	124
1.	Miscible Displacement	124
2.	Selection of a Mathematical Model	125

III.	The Lapidus-Amundson Model	125
A.	The Equation	125
B.	Parameter Estimation	127
1.	General Procedure	127
2.	Error of Calculations	127
C.	Vertical Movement of Polluting Metals	127
D.	Velocity Estimation Procedure	128
E.	Development of Equations for Prediction	128
1.	Multiple Regression Analysis	128
2.	Soil and Leachate Properties in the Regression Analysis	130
3.	Predictive Equations	130
IV.	Error Function Model	131
A.	Solute Profile	131
B.	Defining the Model	133
C.	Regression A and D_e to Soils and Leachate Properties	134
1.	Factor A	136
2.	Factor D_e	136
V.	Application of Predictive Equations	136
A.	Example Using L-A Model	136
B.	Example Using E-F Model	138
C.	Interpretation of Results	140

References	140
------------------	-----

Chapter 6

Effect of Hydrogen Ion Concentration of Acid Wastes on Soils	143
I. Introduction and Scope	143
II. Materials and Methods	145
A. Materials	145
1. Soils	145
2. Acids (Reagent Grade)	146
3. Spent Acid Wastes	146
4. Municipal Solid Waste Leachate	147
B. Methods	147
1. Soil Columns	147
2. Effluent Analyses	148
3. Soil Analyses	148
III. Effect of Water, Dilute Acids, and MSW Leachates on Soils	148
A. Water	148
B. Sulfuric Acid at pH 3.0	151
C. $AlCl_3 \cdot FeCl_2$ at pH 3.0	151
D. Municipal Solid Waste Landfill Leachate	152
IV. Effects of Strong Inorganic Acids on Soil	152
A. Nitric Acid at 2 N	156
1. Column Flow Characteristics	156
2. pH of Soil Column Effluent	158

3.	Movement of Soil Constituents	158
B.	Sulfuric Acid at 2 <i>N</i>	158
1.	Column Flow Characteristics	158
2.	pH of Soil Column Effluent	158
3.	Movement of Soil Constituents	159
C.	Phosphoric Acid at 6 <i>N</i> and 8.8 <i>N</i>	159
1.	Column Flow Characteristics	159
2.	pH of Soil Column Effluents	159
3.	Movement of Soil Constituents	159
V.	Effects of Strong Organic Acids on Soil	162
A.	Acetic Acid at 2 <i>N</i>	162
1.	Column Flow Characteristics	162
2.	pH of Soil Column Effluent	162
3.	Movement of Soil Constituents	162
B.	Soil Permeability as Influenced by Bulk Density of Soil	164
VI.	Effects of Strong Spent-Acid Waste on Soil	164
A.	Spent Nitric Acid, 2 <i>N</i> — Sylvania™	165
1.	Column Flow Characteristics	165
2.	pH of Soil-Column Effluent	167
3.	Movement of Soil Constituents	167
B.	Spent Nitric Acid 2 <i>N</i> — Wolverine™	173
1.	Column Flow Characteristics	173
2.	pH of Soil Column Effluent	173
3.	Movement of Soil Constituents	173
C.	Spent Sulfuric Acid 1 <i>N</i> — Cyprus Bagdad	176
1.	Column Flow Characteristics	176
2.	pH of Soil Column Effluent	176
3.	Movement of Soil Constituents	176
D.	Spent Phosphoric Acid 8.8 <i>N</i> and 6 <i>N</i> — Brightening Mix	180
1.	Column Flow Characteristics	180
2.	pH of Soil Column Effluent	180
3.	Movement of Soil Constituents and Spent Acid Metals	180
VII.	Discussion	180
A.	The Soil	182
1.	Natural Soil Constituents	182
2.	Soil pH	182
3.	Soil Texture.....	182
4.	Lime Content	183
5.	Specific Mineral Species and Salts.....	183
B.	The Vehicle of Transport.....	183
1.	Factors Affecting Constituent Solubility and Soil Permeability	183
2.	Concentration Effects of the Acids.....	183
3.	Potential Pollutants in Spent Acid	184
4.	Reduction/Oxidation Reactions.....	184
5.	Kind of Acid Vehicle	184
C.	The Polluting Constituent	185
1.	Cations.....	185

2.	Anions	185
D.	Soil Failure/Stabilization	185
References.....		187

SITE SELECTION, MONITORING AND CLOSURE

Chapter 7

Site Selection, Monitoring, and Closure		191
I.	Rationale and Scope	191
II.	Site Selection	191
A.	General Criteria	192
B.	Types of Land Disposal	193
C.	General Steps to Site Selection.....	193
1.	Approach	194
III.	Monitoring.....	201
A.	General Criteria	201
1.	Premonitoring.....	202
2.	Monitoring during Disposal.....	203
3.	Postmonitoring.....	203
B.	Waste Properties	203
C.	Landscape and Topography	203
D.	Soil Properties.....	204
1.	Physical.....	204
2.	Chemical.....	204
E.	Hydrology and Geohydrology	204
1.	Well Monitoring	205
2.	Water Quality Monitoring.....	206
F.	Soil Erosion	208
IV.	Closure	211
A.	General Criteria	211
B.	Burials	213
C.	Encapsulations.....	213
D.	Well Injections	213
E.	Land Treatment/Utilization	214
References.....		215

APPENDIXES

USDA and USCS Particle Classifications	219
English — SI Conversion Constants	222
Abbreviations, Signs, and Symbols	223
INDEX.....	229

A cloak of loose, soft material, held to the earth's hard surface by gravity, is all that lies between life and lifelessness. Crumbling rock, grit and grime, and decaying residue — abrading by wind and water — weather into soil — Mother Earth. This loose hide lives — yields, yet does not yield to the forces of climate, having formed through the ages from meteorological, geological, and biological action on rock. The soil not only was born out of fire, flood, and ice but it lives and continues to renew life. At first, animal and plant residues decayed into simpler constituents, renewing nutrient elements available for new life in a perpetual cycle, but now, wastes accumulating from the population bulge of human beings add serious proportions to the burden of cycling and recycling.

Wallace H. Fuller
Soils of the Desert Southwest
University of Arizona Press, 1975

Soils Involved with Waste Burials



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

Chapter 1

LANDFILLS, TRENCHES, ENCAPSULATIONS, AND OTHER BURIALS

I. RATIONALE AND SCOPE

Burial of solid wastes in the ground is still a viable option for disposal of much of our solid waste materials. Sensitivity of society to uncontrolled ocean and land surface dumping is keen, and legislation prohibiting such operations is continually being written into more restrictive language. Moreover, new and innovative procedures of disposal, e.g., pyrolysis, recycling, chemical combining, and even the better-known composting and incineration methods, represent volume reductions in need of final land disposal. The demand for acceptable burial techniques and methods, therefore, must remain as one of our top waste disposal priorities. The sanitary landfill, trenching, encapsulation, and other burial methods have formed a part of society's disposal program for a long time, but there has been small improvement in acceptability for environmental pollution control. The lagging in development of better burial techniques has not been due as much to indifference by the communities or industries as to lack of knowledge of complex physical and biological systems. These include

1. Soil-waste reactions (chemical, physical, and biological) under both controlled and natural conditions
2. Migration rates of specific pollutants (heavy metals, organic compounds, and organic solvents) through the complex-porous soil medium
3. Loading or concentration factors
4. The host of highly different potential pollutants in a single waste stream
5. The way one constituent affects another with respect to attenuation or retention in soils

Furthermore, the classes of waste generated, including municipal, industrial, institution, hospital, pollution control residues, construction and demolition, and agricultural wastes, constantly change in amount and composition with time. Improvement is needed in all areas of (a) planning, (b) financing, (c) public interest, and (d) technical guidance, if environmental pollution of the surface and groundwater and soil, air, and streams are to remain within acceptable limits.

Burial of wastes under controlled conditions has yet to reach the state where there is absolute assurance of complete environmental protection. A need exists, therefore, to provide more and better environmental safeguards and maintenance of a higher quality of landfill operations to minimize groundwater pollution, air pollution, surface water pollution, and health hazards.

The historic effects of improper disposal of our nations hazardous solid wastes have become today's environmental problems requiring remedial action. This underscores the necessity to plan carefully and safely for any land disposal. Because the design involves excavation below the earth surface, the normal soil buffering thickness that protects underground water and lateral movement of solutions is lessened. Attention to this potentially dangerous circumstance, therefore, must play a foremost part in the sound design from all burials.

II. SANITARY LANDFILL

A. Scope

The sanitary landfill described by the American Society of Civil Engineers constitutes a

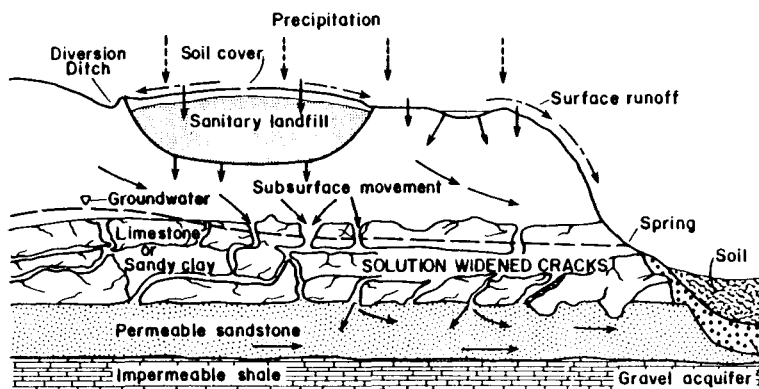


FIGURE 1. Leachate and infiltration movement are influenced by the kind of soil and geologic rock formations such as limestone. (Modified from Brunner, D. R. and Keller, D. J., *Sanitary Landfill Design and Operation*, Solid Waste Management Series, SW-65ts, U.S. Environmental Protection Agency, Washington, D.C., 1972, 13.)

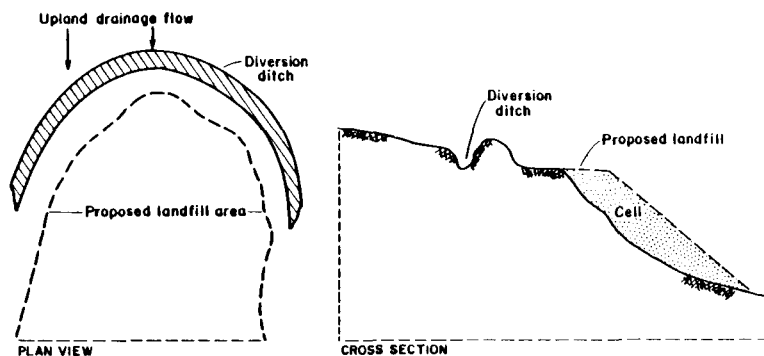


FIGURE 2. Two views of the position of a diversion ditch to intercept and transport upland drainage around a proposed sanitary landfill.

disposal of refuse on land, without creating nuisances to public health or safety, by utilizing the principles of engineering to confine refuse to the smallest practical area, to reduce it to the smallest practical volume, and to cover it with a layer of soil at the conclusion of each day's operation, or at a more frequent interval if necessary (Figures 1 and 2).¹ Additional constraints have been added by the American Public Works Association:²

1. Minimize the possibility of polluting surface and groundwater.
2. Minimize vector breeding or sustenance by eliminating all possible harborage and food supply for rats, flies, and other vermin.
3. Minimize fire hazard.
4. Adequately deal with the possibility of direct disease transmission (e.g., control of trichinosis by not allowing swine to feed on infected garbage).
5. Effectively control air pollution, such as smoke and odors.
6. Effectively control nuisance factors (i.e., the system must be aesthetically acceptable and noise must be held to a minimum).

B. Development

The evolution of the sanitary landfill probably followed the sequence of casual discard

of unwanted items → open dumping → closed landfill → controlled burial that meets established standards of aesthetics, environment, and public health. Shredding, pulverizing, and baling now add to the sophistication of the modern concept of the sanitary landfill. Open burning to reduce the volume of solid waste is being phased out of land burial operations just as is open dumping. The public demands better solid waste disposal practices now than at any time in history.

C. Limitations

The carefully planned sanitary landfill can still offer serious problems for the environmental qualities of the surroundings. The composition of the gases and leachates generated during biodegradation varies primarily according to the availability of oxygen which can change abruptly according to a number of factors difficult to control. The quality of groundwater and surface water can be degraded by landfill leachate infiltrating the soil and unconsolidated vadose zone, unless precautions are taken to select suitable sites and not overload the capacity of the soil to attenuate (or retain) the potential pollutants. The importance of the kind of soil used for daily cover (20% of fill volume) and final closure cover (5 to 10%) is overlooked too frequently and has led to failure of pollutant confinement to the site facility. Proper site selection, therefore, assumes an absolutely essential part of a successful sanitary landfilling program.

Only recently has it become clear that certain forms of waste materials are unsuitable for disposal in a sanitary landfill. Too often leaks of toxic chemicals, of low biodegradability at the disposal levels, have reached groundwater supplies. Landfill burials of hazardous chemicals, including pesticide wastes, no longer share the confidence of safe disposal provided for other solid wastes. This is largely because the detoxification mechanisms and rates of biodegradation as well as to the ultimate attenuation by the soil are not completely understood. Assessment of the consequences to the environment of these toxic land disposals is not fully possible. Key factors include volatility, leaching, migration, nature and rate of the detoxification process, and residual toxicity. Particularly deficient is quantitative information concerning the capacity of the various types of soil to attenuate, retain, modify, and degrade hazardous chemicals and pesticides reaching the soil surface and burial facilities.

D. Site Selection

Sanitary landfill site selection is just as complex and critical as that for land treatment discussed in the previous sections. The soil assumes a key position in pollutant control (Tables 1 and 2) along with the kind of solid waste being considered. Both determine the site characteristics most desirable for pollutant containment. Some very hazardous solid wastes are best presumed to be unsuitable landfill for disposal. This includes many chemically treated, stabilized/solidified wastes.³ In selection of a site for a sanitary landfill (SLF) certain requirements must be met. The facility must provide:

1. Long-term protection of the quality of surface and subsurface waters from any of the hazardous constituents disposed therein and from any hazards to the public health and environment
2. No direct hydraulic continuity with surface and subsurface waters
3. Protection from subsurface flow of groundwater into the disposal area
4. Protection from surface flow into the area (compare Figure 2)
5. Control of leachate generation and means for collecting and suitably disposing of any leachate formed
6. Monitoring wells capable of estimating the dissemination of leachate constituents

Where hazardous materials are present in the waste, these requirements necessitate meticulous

Table 1
UNIFIED SOIL CLASSIFICATION SYSTEM AND CHARACTERISTICS PERTINENT TO SANITARY LANDFILLS

Major divisions	Classes		USDA	Name	Potential frost action	Drainage characteristics ^a	Value for embankments	Permeability (cm/sec)	Compaction characteristics ^b	Std AASHTO Max unit dry weight ^c 16/ft ³	Requirements for seepage control
	USCS										
Coarse-grained soils Gravel and gravelly soils	GW	Gravel		Well-graded gravels or gravel-sand mixtures, little or no fines	None to very slight	Excellent	Very stable, pervious shells of dikes and dams	$k > 10^{-2}$	Good, tractor, rubber-tired, steel-wheeled roller	125—135	Positive cutoff
	GP	Very gravelly loamy sand		Poorly graded gravels or gravel-sand mixtures, little or no fines	None to very slight	Excellent	Reasonably stable, pervious shells of dikes and dams	$k > 10^{-2}$	Good, tractor, rubber-tired, steel-wheeled roller	115—125	Positive cutoff
Sand and sandy soils	GM	Gravelly loamy sand		Silty gravels, gravel-sand-silt mixtures	Slight to medium	Fair to poor Poor to practically impervious	Reasonably stable, not particularly suited to shells, but may be used to impervious cores or blankets	$k = 10^{-3} - 10^{-6}$	Good, with close control, rubber-tired, sheepfoot roller	120—135	Toe trench to none
	GC	Gravelly sandy clay		Clayey gravels, gravel-sand-clay mixtures	Slight to medium	Poor to practically impervious	Fairly stable, may be used for impervious core	$k = 10^{-6} - 10^{-8}$	Fair, rubber-tired, sheepfoot roller	115—130	None
Sand and sandy soils	SW	Coarse sand		Well-graded sands or gravelly sands little or no fines	None to very slight	Excellent	Very stable, pervious sections slope protection required	$k > 10^{-3}$	Good, tractor	110—130	Upstream blanket and toe drainage or wells
	SP	Sand		Poorly graded sands or gravelly sands, little or no fines	None to very slight	Excellent	Reasonably stable, may be used in dike section with flat slopes	$k > 10^{-3}$	Good, tractor	100—120	Upstream blanket and toe drainage or wells
	SM	Fine sand		Silty sands, sand-silt mixtures	Slight to high	Fair to poor Poor to practically impervious	Fairly stable, not particularly suited to shells, but may be used for impervious cores or dikes	$k = 10^{-3} - 10^{-6}$	Good with close control, rubber-tired, sheepfoot roller	110—125	Upstream blanket and toe drainage or wells
	SC	Clayey sand		Clayey sands, sand-clay mixtures	Slight to high	Poor to practically impervious	Fairly stable, use for impervious core for flood control structures	$k = 10^{-6} - 10^{-8}$	Fair, sheepfoot roller, rubber-tired	105—125	None

Fine-grained soils
Silt and clays,
LL is less than 50

ML	Silt and silt loam	Inorganic silts and very fine sands rock flour, silty or clayey fine sands or clayey silts with slight plasticity	Medium to very high	Fair to poor	Poor stability, may be used for embankments with proper control	$k = 10^{-6}$ to 10^{-5}	Good to poor, close control essential, rubber-tired roller, sheepfoot roller	95—120	Toe trench to none
CL	Silty clay loam	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	Medium to high	Practically impervious	Stable, impervious cores and blankets	$k = 10^{-8}$ to 10^{-6}	Fair to good, sheepfoot roller, rubber-tired	95—120	None
OL	Mucky silt loam	Organic silts and organic silt-clays of low plasticity	Medium to high	Poor	Not suitable for embankments	$k = 10^{-6}$ to 10^{-4}	Fair to poor, sheepfoot roller	80—100	None
MH	Silt loam micaceous	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	Medium to very high	Fair to poor	Poor stability, core of hydraulic dam, not desirable in rolled fill construction	$k = 10^{-6}$ to 10^{-4}	Poor to very poor, sheepfoot roller	70—95	None
CH	Silty clay loam	Inorganic clays of high plasticity, fat clays	Medium	Practically impervious	Fair stability with flat slopes, thin cores, blankets, and dike sections	$k = 10^{-8}$ to 10^{-6}	Fair to poor, sheepfoot roller	75—105	None
OH	Mucky silty clay	Organic clays of medium to high plasticity, organic silts	Medium	Practically impervious	Not suitable to embankments	$k = 10^{-8}$ to 10^{-6}	Poor to very poor, sheepfoot roller	65—100	None
Pt	Muck and peats	Peat and other highly organic soils			Not recommended for sanitary landfill construction				

^a Values are for guidance only; design should be based on test results.

^b The equipment listed will usually produce the desired densities after a reasonable number of passes when moisture conditions and thickness of lift are properly controlled.

^c Compacted soil at optimum moisture content for Standard AASHTO (Standard Proctor) compactive effort. Multiply by 16.02 to convert to kg/m³.

Modified from Brunner, D. R. and Keller, D. J., Sanitary design and Operation, Solid Waste Management Series, SW-65ts, U.S. Environmental Protection Agency, Washington, D.C., 1972, 59.

Table 2
SUITABILITY OF GENERAL SOIL TYPES AS COVER MATERIAL^a

Function	Clean gravel	Clayey-silty gravel	Clean sand	Clayey-silty sand	Silt	Clay
Prevent rodents from burrowing or tunneling	G	F—G	G	P	P	P
Keep flies from emerging	P	F	P	G	G	E ^b
Minimize moisture entering fill	P	F—G	P	G—E	G—E	E ^b
Minimize landfill gas venting through cover	P	F—G	P	G—E	G—E	E ^b
Provide pleasing appearance and control blowing paper	E	E	E	E	E	E
Grow vegetation	P	G	P—F	E	G—E	F—G
Be permeable for venting decomposition gas ^c	E	P	G	P	P	P

^a E, excellent; G, good; F, fair; P, poor.

^b Except when cracks extend through the entire cover.

^c Only if well drained.

Note: Based on USCS classification.

From Brunner, D. R. and Keller, D. J., Sanitary Design and Operation, Solid Waste Management Series, SW-65ts, U.S. Environmental Protection Agency, Washington, D.C., 1972, 59.

attention to detail in every category as well as in care and maintenance of the site facility. For example, for low levels of hazardous waste, soil thickness presumably may be less than for an intermediate or higher level of hazardous waste. Specific characteristics of the waste and site are interdependent. They must be considered together in selecting land for SLF facilities, including site testing, design, size, site repair and modification, nature and time of closure, and for general economic analysis.

The establishment of undisputed guidelines cannot be wholly complete at this time, since large gaps persist in our knowledge of the sanitary landfill potential for safe and secure hazardous waste disposal. In addition, personal concepts of what constitutes a real threat exist. The purpose here is primarily to synthesize knowledge on the soil characteristics most suitable for the establishment of sanitary landfills and to suggest soil manipulations that can minimize movement of potential pollutants (Figure 2).

An outline is provided to illustrate the magnitude of the criteria necessary to establish an acceptable SLF:

Wastes suitable for the sanitary landfill

Factors in site selection for the sanitary landfill

Geographic location

- Relationship to waste generation and/or collection
- Relationship to community
- Relationship to water sources

Environmental characteristics

- Soils
- Topography
- Climate
- Groundwater
- Surface water

- Geology
- Soil, water, and wind erosion
- Land acquisition and control
 - Purchase option
 - Lease option
 - Control factors for the sanitary landfill
- Landfill options
 - Sanitary landfill method
 - Encapsulation method
 - Trench method
- Land repair, soil and water erosion control
- Building, equipment, and roads
- Monitoring
 - Premonitoring
 - Monitoring during disposal
 - Postmonitoring
- Public relations
- Final disposition of the SLF area
- Environmental impact

E. The Soil

Solid wastes may be deposited into a sanitary landfill facility in a number of different ways. The specific method selected depends on the nature of the site and the waste. Since environmental conditions differ so much from one climatic region to another and even within a single region, no two disposal sites will be the same. Similarly, solid wastes vary from industry to industry and community to community and no two waste streams are identical. Fortunately, environmental factors such as soil, precipitation, topography, and others can function under a variety of circumstances to minimize pollutant migration. Moreover, within the major environmental components, the soil (or porous medium through which the pollutant may move or be retained), the leachate (or vehicle of transport), and the polluting constituents, certain measurable basic properties are common that can be sorted out, identified, and combined to minimize pollutant solubility and movement.

The soil plays a paramount role in the site facility of the sanitary landfill or any burial of waste (Tables 2 and 3). Soil virtually encapsulates the solid waste (Figure 3). The “cell” encasement provides another way soil can be used to help minimize migration of constituent from solid waste operations (Figure 4). A cell is compacted waste and soil encasement oriented in a series of adjoining cells all of the same height to make up a “lift”. No fixed height of a cell is suggested, but range from about 3 to 10 m. The surface area should be kept at a minimum to conserve soil since the cell configuration can greatly influence the volume of cover. All soils are not equally effective in attenuating or retaining pollutants, as has been discussed in the first few chapters of this book. The medium textured soils, such as those classed as loams by the U.S. Department of Agriculture (USDA) system (50% sands and 50% silt and clay with about equal proportions of each), appear to be the most desirable (Table 4). In general, the finer the texture in mineral soils, the greater is the capacity to retain pollutants. However, soils high in clay have the distinct disadvantage of unusually slow drainage, allowing water to collect in the disposal excavation and accumulate leachates. Sandy soils characteristically allow unrestricted flow of leachate, permit rapid drainage, but have little capacity to retain pollutants and even fine suspended matter. Obviously these two extreme soil textures are least suited for burial methods of solid wastes. The soil texture characteristics must be coarse enough to prevent water from filling and overflowing, like an impoundment, but fine (clayey) enough to attenuate heavy metals and

Table 3
RANKING OF USCS SOIL TYPES ACCORDING TO PERFORMANCE OF COVER FUNCTIONS

USCS symbol	Typical soils	Trafficability			Water percolation			Gas migration		
		Go-No Go (RCI value) ^a	Stickiness (clay, %)	Slipperiness (sand-gravel, %)	Impede (k, cm/s) ^a	Assist (k, cm/s) ^a	Impede (H _c , cm) ^a	Assist (H _c , cm) ^a	Same H _c values as for Impede Gas Migration	Same k values as for Impede Water Percolation
GW	Well-graded gravels, gravel-sand mixtures, little or no fines	I (>200)	I (0—5)	I (95—100)	X (10 ⁻²)	III	X (6)	I		
GP	Poorly graded gravels, gravel-sand mixtures, little or no fines	I (>200)	I (0—5)	I (95—100)	XII (10 ⁻¹)	I	IX	II		
GM	Silty gravels, gravel-sand-silt mixtures	III (177)	III (0—20)	III (60—95)	VII (5 × 10 ⁻⁴)	VI	VII (68)	IV		
GC	Clayey gravels, gravel-sand-clay mixtures	V (150)	VI (10—50)	V (50—90)	V (10 ⁻⁴)	VIII	IV	VII		
SW	Well-graded sands, gravelly sands, little or no fines	I (>200)	II (0—10)	II (95—100)	IX (10 ⁻³)	IV	VIII (60)	III		
SP	Poorly graded sands, gravelly sands, little or no fines	I (>200)	II (0—10)	II (95—100)	XI (5 × 10 ⁻²)	II	VII	IV		
SM	Silty sands, sand-silt mixtures	II (179)	IV (0—20)	IV (60—95)	VIII (10 ⁻³)	V	VI (112)	V		
SC	Clayey sands, sand-clay mixtures	IV (157)	VII (10—50)	VI (50—90)	VI (2 × 10 ⁻⁴)	VII	V	VI		
ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts with slight plasticity	IX (104)	V (0—20)	VII (0—60)	IV (10 ⁻⁵)	IX	III (180)	VIII		
CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	VII (111)	VIII (10—50)	VIII (0—55)	II (3 × 10 ⁻³)	XI	II (180)	IX		
OL	Organic silts and organic silty clays of low plasticity	X (64)	V (0—20)	VII (0—60)	—	—	—	—		
MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	VIII (107)	IX (50—100)	IX (0—50)	III (10 ⁻⁷)	X	—	—		

CH	Inorganic clays of high plasticity, fat clays	VI (145)	X (50—100)	X (0—50)	I (10 ⁻⁶)	XII	I (200—400+)	X
OH	Organic clays of medium to high plasticity, organic silts	XI (62)	—	—	—	—	—	—
Pt	Peat and other highly organic soils	XII (46)	—	—	—	—	—	—

USCS symbol	Fire resistance	Erosion control		Dust control	Reduce freeze action		Crack resistance (expansion, %)
		Water (K-factor) ^a	Wind (sand-gravel, %)		Fast freeze (H _c , cm) ^a	Saturation (heave, mm/day)	
OL	Same as Impede Gas Migration	XI (0.21—0.29)	VII (0—60)	Same ranking and values as for Wind Erosion Control	—	VIII	VII
GW		I (<0.05)	I (95—100)		X	I (0.1—3)	I (0)
GP		I	I (95—100)		IX	I (0.1—3)	I (0)
GM		IV	III (60—95)		VII	IV (0.4—4)	III
GC		III	V (50—90)		IV	VII (1—8)	V
SW		II (0.05)	II (95—100)		VIII	II (0.2—2)	I (0)
SP		II	II (95—100)		VII	II (0.2—2)	I (0)
SM		VI	IV (60—95)		VI	V (0.2—7)	II
SC		VII (0.14—0.27)	VI (50—90)		V	VI (1—7)	IV
ML		XIII (0.60)	VII (0—60)		III	X (2—27)	VI
CL	XII (0.28—0.48)	VIII (0—55)	II	VIII (1—6)	VIII (1—10)		

Same as Impede Gas Migration

Same ranking and values as for Wind Erosion Control

Table 3 (continued)
RANKING OF USCS SOIL TYPES ACCORDING TO PERFORMANCE OF COVER FUNCTIONS

USCS symbol	Fire resistance	Erosion control		Dust control	Reduce freeze action			Crack resistance (expansion, %)
		Water (K-factor) ^a	Wind (sand-gravel, %)		Fast freeze (H _c , cm) ^a	Saturation (heave, mm/day)		
MH		X (0.25)	IX (0-50)		—	IX		IX
CH		IX (0.13-0.29)	X (0-50)		I	III (0.8)		X (>10)
OH		VIII	—		—	—		IX
Pt		— V (0.13)	—		—	—		—

USCS symbol	Side slope			Impede vector emergence	Discourage birds	Support vegetation	Future use	
	Stability	Seepage	Drainage				Natural	Foundation
GW	Determine on basis of laboratory testing	Same ranking and values as for Impede	Water Percolation	X		X	Same ranking as for Support Vegetation	Same ranking and values as for Go-No Go
GP								
GM								
GC								
SW	Determine on basis of laboratory testing	Same ranking and values as for Impede	Water Percolation	VIII	All soils are suitable	VI	Same ranking as for Support Vegetation	Same ranking and values as for Go-No Go
SP				V		V		
SM				IX		IX		
SC				IX		XI		
ML				II		II		
CL				IV		I		
OL				VI		III		
MH				III		IV		
CH				VI		IV		
OH				II		VIII		
Pt				I		VIII		
				—		III		

^a RCI is rating cone index, k is coefficient of permeability, H_c is capillary head, and K-factor is the soil erodibility factor. The ratings I to XIII are for best through poorest in performing the specified cover function.

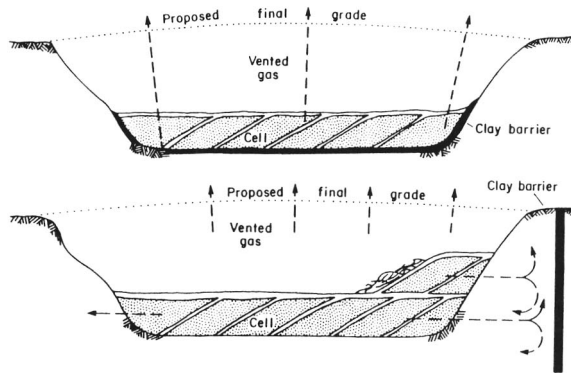


FIGURE 3. Illustration of clay as liner in an excavation or installed as a wall barrier to block underground gas flow. (From Brunner, D. R. and Keller, D. J., *Sanitary Landfill Design and Operation*, Solid Waste Management Series, SW-65ts, U.S. Environmental Protection Agency, Washington, D.C., 1972, 26.)

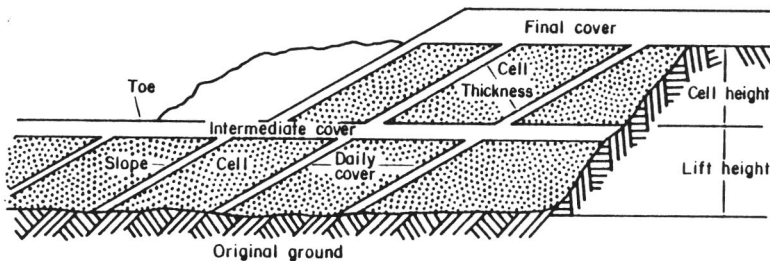


FIGURE 4. The cell is the common building block in sanitary landfilling. Solid waste is spread and compacted in layers within a confined area. At the end of each working day, or more frequently, it is covered completely with a thin, continuous layer of soil, which is then also compacted. The compacted waste and soil constitute a cell. A series of adjoining cells makes up a lift. The completed fill consists of one or more lifts. (From Brunner, D. R. and Keller, D. J., *Sanitary Landfill Design and Operation*, Solid Waste Management Series, SW-65ts, U.S. Environmental Protection Agency, Washington, D.C., 1972, 27.)

other pollutants of the leachate to prevent them from moving into the groundwater. The excavation pit becomes the outer shell of the sides and bottom of the encapsulated waste. The lower soil barrier should be no thinner than 2 m above the historic upper limit of the capillary fringes of the groundwater. Often overlooked in site selection is the location of possible aquifers passing under a part of or the whole of a landfill facility. Such land areas should be avoided.

1. Landfill Liners

In addition to the selection of a suitable site with acceptable soil for the sides and bottom of the SLF pit, the excavation soil also should be acceptable for liner and cover purposes (Figures 3 and 4). Liners are discussed in much greater detail in Chapter 2. A series of test holes to a depth of at least 3 m below the proposed floor should be made and the soil sampled at every 30 cm (or whenever a change in particle size distribution occurs) for mechanical analysis (sand, silt, and clay), electrical conductivity, and pH analysis. Textures of the vertical soil profile can then be plotted to identify prominent surfaces. The different soil surfaces may then be used as a guide during excavation and layers of soil of the most desirable quality identified and stockpiled for lining, cover, and closure purposes.

Table 4
SOIL PROPERTIES AFFECTING THE USE OF LAND FOR SANITARY
LANDFILLS AND CRITERIA FOR RATING THE DEGREE OF SOIL
LIMITATIONS IMPOSED BY THE SOIL PROPERTIES

Parameter	Degree of soil limitation	Criteria ^a		Remarks
1. Permeability	Slight	Less than 2.0 in./hr		None
	Moderate	2.0 to 6.3 in./hr		
	Severe	More than 6.3 in./hr		
2. Depth to seasonal high water table	Slight	More than 4 ft		Well- and some moderately well-drained soil classes
	Moderate	1 to 4 ft		Somewhat poorly and some moderately well-drained soil classes
	Severe	Less than 1 ft		Poorly and very poorly drained soil classes
3. Soil	Slight	Sandy loams, loam, silt loam, sandy clay loam		Gravelly analogs of these textures would have the same rating
	Moderate	Silty clay loam, clay loam, sandy clay, loamy sand, silt		
	Severe	Silty clay, clay, muck, peat, sand, gravel		
4. Flood hazard	—	—		Soils that are subject to flooding have severe limitations
5. Depth to bedrock	Slight	Hard	Rippable	
	Moderate	More than 5 ft	More than 5 ft	None
	Severe	Less than 5 ft	Less than 5 ft	
6. Slope	Slight	0—6%		None
	Moderate	6—12%		
	Severe	More than 12%		
7. Stoniness	Slight	0, 1		Stoniness classes, Soil Survey Manual; stones are more than 10 in. in diameter
	Moderate	2		
	Severe	3, 4, 5		
8. Trafficability	—	—		Most soils that are sufficiently impervious for sanitary landfills have textures resulting in trafficability limitations when wet

^a Multiply inches by 2.54 to convert to centimeters.

Multiply feet by 0.3048 to convert to meters.

From U.S. Department of Agriculture, Soil Conservation Service, Hydrology, SCS National Engineering Handbook, Sect. 4, U.S. Department of Agriculture, Washington, D.C., 1972, chap. 4.

Where soil depths are shallow (or the predominate soils are coarse textures such as gravels, sands, etc.), lining the SLF with soils capable of fulfilling the function of a barrier to pollutant migration to groundwater levels must be undertaken. Small differences in clay (<2 μm) content can make appreciable differences in the capacity of the soil to attenuate heavy metals and other pollutants. Important physical characteristics of soils used as liners include texture, homogeneity (soils may require mechanical mixing prior to lining), and compactability.

The advantages of soil-liner use is widely recognized for waste disposal containment. All soil materials that fulfill containment functions may be considered liners.⁴ Some liners must be impermeable to water and associated contaminants. They must maintain a structural integrity until the waste has stabilized and the potential for leachate generation has fallen to safe limits. More than 60% of landfills in the U.S., for example, generate leachate during their lifetime. Haxo has provided a diagram (Figure 5) to show the concept of an impervious

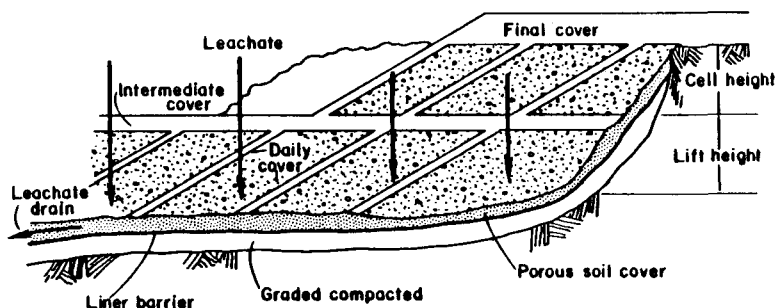


FIGURE 5. The concept of lining a sanitary landfill using both soil and nonsoil liners as seals. (From Haxo, H. E., *Gas and Leachate from Landfills — Formation, Collection and Treatment*, U.S. EPA-600/9-76-004, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1976, 130.)

barrier as liner for a landfill. Soils can be used either with impervious or pervious liners. In the absence of a fabricated chemical liner barrier, the soil itself becomes the liner. The usefulness depends upon the nature of the liner material as it may interact with the environment in which it is expected to operate. In those instances where the management plan requires complete containment of leachate so that it may be pumped into a separate treatment (e.g., aeration pond) system, special soil manipulation is required, just as with liner systems that are designed to leak.⁴

One of the oldest materials for pond, lake, lagoon, or drainage ditch lining is bentonite clay for sealing against outflow. Bentonite clay, being a montmorillonite type of expanding lattice structure, changes volume upon wetting and drying. Where wetting and drying occur, such as around the edges of leachate levels, these types of clays crack. Leaks appear more frequently with the montmorillonites, under wetting and drying conditions, than when nonexpanding lattice clays such as kaolinite and illite are used. Under constantly wet conditions, on the other hand, montmorillonite clays may be equally as effective as others.⁵ To import enough bentonite clay to prevent water movement through closed disposal sites may be expensive. In an 18.6-ha (46 acre) experimental site in Kansas City, sponsored by the EPA as a demonstration, 45.7 cm (18 in.) of bentonite-containing clay liner was installed at a cost of about \$2930/ha (\$1185/acre) in 1970. Pure bentonite, undoubtedly, would be more expensive.

Fine-textured native soils have been used since 1960 by the first author as liner sealants for permanent lake establishment. Fine-textured soils (at least 20% clay and 15 meq/100 g CEC) may be available from the excavation site and stockpiled or imported to the site and compacted as a liner (Figure 5). Compaction to permeabilities less than 10^{-6} cm/s are possible for containment of aqueous solutions such as solid waste leachates (Table 1). Wetting the soil to about 40% of its normal field water holding capacity during the compacting procedure aids materially in achieving the desired bulk density.

Disposal sites for municipal solid waste often do not require complete sealing. In fact, some leakage is desirable to prevent overflow and help stabilize the waste mass. Sites located in sandy and gravelly soils, and where the soil layers are thin, require soil lining since pollutant retention in such soil is poor. A soil barrier thickness of 1 to 1.5 m (4 to 5 ft), depending on the nature of the waste leachate, rainfall, clay content of the soil, etc., may be used successfully with only modest compaction to minimize migration of pollutants. This soil layer should be at least 1.5 m (5 ft) above the annual average level of the water table. Crushed limestone, and organic wastes such as bioresistant nut hulls, may be used along with infiltrating soil liners to further discourage migration of trace and heavy metals.⁴ Landfills and other closed drainage systems should be located and managed such that the soil depth

(soil liner) is compatible with the waste to be deposited. A 3-m layer (or 10 ft) of natural in-place soil is suggested as lining for most closed systems, provided the soil layer is of medium texture or finer. Sands, gravels, and rock have little to no effective retention properties for constituents in solution from leachates and other aqueous vehicles.

Soil is also used to complement other types of liners for

1. Attenuation purposes
2. Stabilizing support of fragile chemical liners
3. Mixing with lining materials such as cements and asphalts
4. Mixing with other sealants containing chemicals, lime, rubber and plastic latexes, and penetrating polymeric emulsions (Figure 5)

Sandy soil was used on top of asphalt liners by a Pennsylvania firm to protect the liner and allow a flow path for the leachate to a collection manhole at the bottom of the landfill.⁶ The predicted life of asphalt placed in this manner is 50 years, provided certain solvents do not enter the landfill. Haxo suggests a cover of porous soil over the liner barrier and a graded, compacted clean soil liner beneath the liner in his concept of lining a sanitary landfill.⁷

2. Landfill Covers

Natural soils constitute the most abundant and accessible sources of “cover” for solid waste. Soils offer widely differing porosities to control gas and water movement. Soil for cover on waste may be managed in many ways to function effectively, for example, with regard to:

Land Management and Usage

- Minimize settlement and maximize compaction
- Fertilize for vegetation growth
- Minimize soil and water erosion
- Preserve slope stability
- Control water movement

Health Values

- Minimize vector breeding
- Maximize insect control
- Maximize bird and animal usage
- Control water infiltration
- Control harmful gas movement
- Minimize potential fire hazard

Aesthetic Values

- Provide a base for vegetation of desirable appearance
- Control odors
- Control refuse blowing

Thus, soil covers may function in ways that are conflicting or complementary (Figure 6). A clay soil, for example, may be most suited to prevent water penetration into the excavation, but it also will impede desirable gas movement out of the site. Therefore, a priority of functions must be established in the selection of the soil cover. Soil material is unusually flexible in properties effective in the disposal of most wastes. Soils are well classified and delineated by the USDA, Soil Conservation Service, and State Experiment Stations. Different soil types as characterized by the USCS and USDA can be identified and those having the desired properties can be selected (Appendix Tables 1, 2, and 3).

The kind of soil selected for cover also depends on the climate. Erosion control practices,

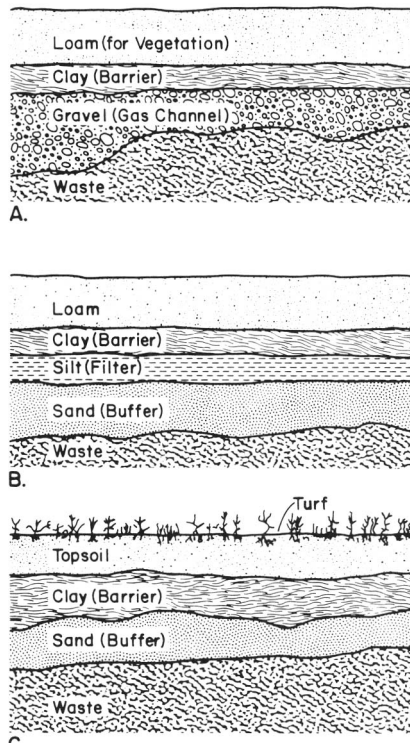


FIGURE 6. Cross sections of three types of layered covers used over sanitary landfills. (A) Allows for gas collection and channelling; (B) permits the establishment of a sand buffer for inflow and outflow of fluids; and (C) is a simplified vegetative-type cover. (Modified from Lutton, R. J., Regan, G. L., and Jones, L. W., Design and Construction of Covers for Solid Waste Landfills, EPA-600/2-79-165, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1979, 66.)

as well as the USDA soil erodibility K-factor, for example, differ by climatic zones. Freezing and thawing, of course, are not as important for soil selection and management in the southern as in the northern climates. Soil types can be readily evaluated for cover functions in any section of the U.S. by contacting the USDA Soil Conservation Service which has soil climatic maps suitable for this purpose. The U.S. EPA (MERL) has prepared a broad ranking of USCS soil types according to cover functions.⁸ Examples of rankings that concern the physical properties of the soil include

1. Texture (sand, silt, and clay, as related to stickiness and slipperiness and trafficability)
2. Water infiltration and penetration
3. Gas exchange rate (ability of the soil to allow gas to escape)
4. Water-holding capacity
5. Erodibility K-factor or the USDA universal soil loss equation (USLE)
6. Fertility and productivity (vegetation establishment factor)

Depth of soil cover will vary with the configuration of the cell and position of the lift.

Table 5
THE MEASURED LANDFILL GAS
COMPOSITION AT MOUNTAIN VIEW,
CALIF.

Measured Gas Composition

Constituent	Volume (%)		
	Average	High	Low
Methane	44.03	46.49	41.38
Carbon dioxide	34.20	36.80	30.73
Nitrogen	20.81	23.51	19.98
Oxygen and argon ^a	0.96	1.69	0.48
Water	Saturated at 14.7 psi and 90°F grains per 100 ft ^{3,b}		
Hydrogen sulfide	0.40	—	0.91
Mercaptan sulfur	0.00	—	0.33
Sulfides	0.41	—	1.80
Disulfides and residuals	0.93	—	1.65

^a Ar represents at least 50% of the total.

^b To convert to ppm multiply by 17, 7, 63, 6.44, 4.75 for H₂S, mercaptan, sulfides, and disulfides, respectively.
 14.7 psi = 1.008×10^5 kg/ms².

From Blanchet, M. S., U.S. Environmental Protection Agency
 OSW, SW-583, 115, 1977.

Usually a 20 cm (8 in.) minimum is required. Fly establishment is prevented by 15 cm of compacted soil. The cell system requires more soil than others, particularly if cell height is shallow. The volume of cover required may even exceed that available at the site depending on the surface area of waste to be covered and thickness. Side slopes ranging from 20 to 30° will minimize the surface area and cover volume.⁵ Cover for the final lift should be deeper than the others, a minimum of 60 cm (2 ft) of compacted soil is recommended. The final cover soil should permit vegetative growth and retain storage water, but be somewhat impervious to water and significant quantities of gases. The analysis of gas from municipal solid waste landfills that appears in Table 5 reveals the presence of CO, CO₂, H₂, CH₄, H₂S, N₂, and small amounts of short chain hydrocarbons. Gas has the capacity to move irregularly through the refuse, the layered soil surrounding the cell, and even through the cover into the atmosphere unless proper ventilation is installed. Movement into open or dry aquifers also allows gas to migrate laterally and even leave the SLF site to collect under vegetation and buildings. Gas-flow through a soil such as SLF cover is described quantitatively in Volume II, Chapter 3. Generally, the object is to manage the soil to keep the flow low.

During the construction of the SLF, designs specific for the chosen site can be very helpful in controlling an acceptable gas exit system. Four main factors important to gas control are

1. Degree of compaction of the soil liner and cover
2. Thickness of the soil liner and cover
3. Particle size distribution of soil selected for the liners and covers
4. Construction of gas barriers, channels, and vents

The importance of compaction of the intermediate and final cover to a specified desired

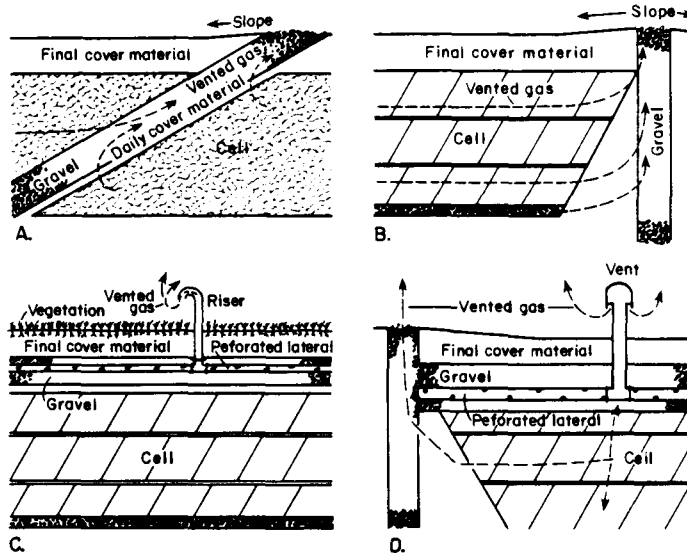


FIGURE 7. Illustrations of vented gas control techniques associated with waste burials, such as sanitary landfills. (A,B) Gravel vents or gravel-filled trenches used to control gas movement; (C) gas vented out of the fill material via pipes that are inserted through a relative impermeable top cover and connected to laterals placed in shallow gravel trenches within or on top of the waste; and (D) two types of vented gas techniques used in conjunction with each other.

density to reduce gas migration to undesired areas and channel to desired exits should be emphasized. The SLF design should include a scheme to control gas through specified compactions. Exit of gas indiscriminately through the final soil cover results in a hazard to the surroundings or damage to vegetation planted to stabilize the soil surface. Cover soil should be compacted at all stages of SLF development including preparation of the final cover. Thin layers of compacted clay placed advantageously may be all that is necessary to satisfy the SLF design for gas control.⁹

The texture (proportion of sand, silt, and clay) is important for proper design of both intermediate and final cover (Figure 6). Fine-textured soils minimize gas compared to coarse gravels and sands. Clays maintain a higher degree of saturation than coarser soils. Yet, where gas flow is required to control proper exit, gravels and coarse sands may be essential to an appropriately vented system (Figure 7).

The final design for the soil cover usually involves the selection of a well-adapted vegetative cover and attention to the establishment of permanent growth. These are discussed in the next section.

In summary, soils function in many ways to contain pollutants of burial disposals, namely,

1. To control surface runoff and accompanying surface erosion selection of suitable soil textures of sand, silt, and clay to resist runoff is one of the key features of a successful cover. The choice of soil cover design and application also is essential for reducing runoff to a minimum. Thus, size, shape, and slope must be important design features, calculated in relation with the local climatic and soil conditions. Other features for runoff and erosion control (Tables 1 and 2) involve soil texture layering and selected use of compaction intensity. Layered soils should be well compacted. Coarse-grained soils can be compacted to 1530 to 2160 kg/m³ and fine grained soils to 1120 to 1920 kg/m³.⁵ Mulching aids in vegetation establishment and persistence and facilitates moisture storage for dry periods.)

2. To control movement of potential pollutants to underground water through attenuation of leachates containing heavy metals, toxic organics, and solvents
3. To control health related factors, such as diseases, bird attraction, fly and vector breeding, and animal breeding and burrowing
4. To reduce the potential of fire hazards
5. To control odors and aerosols
6. To minimize wind erosion and the nuisance of trash blowing and redistribution
7. To establish favorable local aesthetics (A SLF is often considered by the public as a nuisance and obnoxious to the quality of good living.)
8. To facilitate traffic patterns of SLF ingress and egress

3. *Revegetation*

In the guidelines of the U.S. EPA, Office of Solid Waste, the recommendation for revegetation of disturbed land states that a "completed landfill should be covered with 15 cm of clay with permeability less than 1×10^{-7} cm/s or the equivalent, followed by a minimum cover of 45 cm of topsoil to complete the final cover and support vegetation".⁹ Since 45 cm represents a minimum topsoil, deep-rooted plants will require thicker layers of topsoil. Thus, the topsoil depth should be adjusted to the kinds of plants used in revegetation to insure optimum growth and soil protection from the forces of erosion and runoff.

Vegetation functions in many favorable ways for successful SLF closure:

1. Leachate control — reduces precipitation infiltration by enhancing evaporation and transpiration by plants
2. Erosion control — reduces water and wind erosion
3. Cover control — stabilizes cover material with the consequent maintenance of minimum infiltration and leachate generation
4. Gas control — reduction of wetness and water accumulation which in turn lowers the opportunity for gas generation
5. Landscape beautification — the appearance of the SLF can be made pleasant by giving special attention to landscape design and selection of appropriate shrubs and grasses compatible with the climatic environment

The establishment of high-quality permanent vegetation on SLF final cover requires as much attention as successfully establishing landscapes around homes and urban buildings or crops in farm production. The soil must be selected to support optimum growth of plants in:

1. Depth
2. Physical properties, e.g., texture, structure, bulk density, water-holding capacity, and aeration
3. Chemical properties, e.g., pH, cation exchange capacity, soluble salt content, and freedom of toxic substances and indigenous plant diseases
4. Fertility status of N, P, K, and trace nutrients and organic matter

Soil preparation for the final cover is no less demanding than is that for a home garden. Plant selection must be limited to environmentally adapted plants including grasses, shrubs, and trees. Figure 8 is presented to illustrate the need to select climatically adapted plants for each region. Trees are most effective if planted at the periphery of the SLF rather than into the waste disposal area.

Vegetation is extremely sensitive to the gases generated by SLF waste. Damage extends from stunted growth to chlorotic sickly plants, to partial necrosis and dieback, and finally

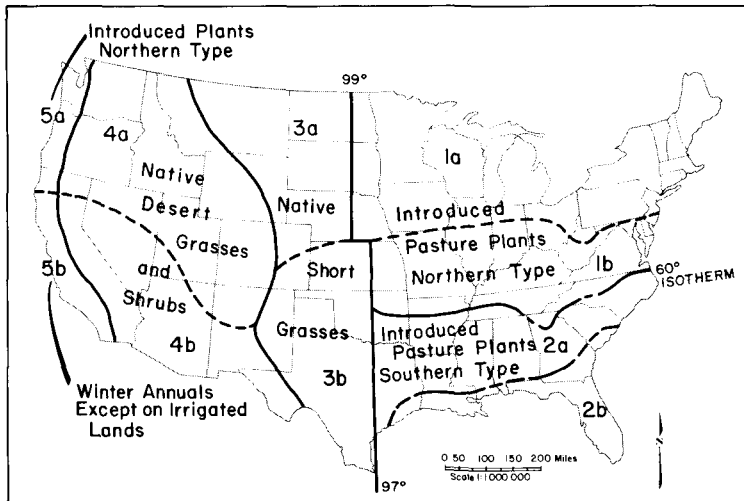


FIGURE 8. A map illustrating five natural pasture regions in the U.S. established primarily on a basis of climate. Divisions of each region into a and b relate primarily to temperate, except 5a and 5b which are separated into the humid northern area and arid southern area. (Modified from Loehr, R. C., Jewell, W. J., Novak, J. D., Clarkson, W. W., and Friedman, G. S., *Land Application of Wastes*, Vol. 1, Environmental Engineering Series, Van Nostrand Reinhold, 1979, chap. 1.)

to death of the whole plant or section of plantings and turf. Vegetation stress may not always be an indication of toxicity due to gases. Other possible factors are drought, shallow root feeding, stony and gravelly spots, toxic material spills, lack of nitrogen or some other fertilizer nutrient, and excessively wet spots due to poor drainage and/or excessive accumulation of water during the rainy season. Lack of homogeneity of the topsoil, depth, and quality, all relate to unevenness of growth, giving a ragged unpleasant appearance. Vegetation management after final closure should be made an essential part of all SLF contracts as well as an ongoing management plan (Table 6).¹⁷ The aesthetic appeal to the public of suitable landscaping should not be overlooked or underestimated (Table 7).¹⁷

Hydroseeding may be the most cost-effective method of seeding. Usually, seeding is followed by mulching with organic residues unless the mulch has been incorporated directly into the hydroseeding operation. Mulch functions to keep the seed from blowing and maintain moisture in the seed zone necessary for germination and seedling establishment. Erosion control is absolutely necessary during seedling establishment. Where slopes are steeper than the usual 2 to 4%, netting or pegging should be used to hold the seed, fertilizer, and mulch in place. Regular maintenance should be required for the first few years of vegetation establishment, since it is not always possible to predetermine the adaptability of vegetation to the microclimate of the specific site.

III. TRENCHES

The trench method of solid hazardous waste disposal is a form of landfilling. Waste is deposited, spread, compacted, and covered in a trench configuration. The cover material is obtained from the excavation of the trench. Trenches are best adapted to flat or gently sloping land. The configuration of the landfill trenches results in a succession of parallel solid waste disposals separated by 1 to 1.5 m of soil wall. Trench length varies from 10 to 100 m for ease of maneuvering equipment with a width of about twice the width of the tractors used for spreading and compacting. Depths usually range from 3 to 4 m, but some are 15 m or

Table 6
SELECTED CHARACTERISTICS OF GRASSES AND LEGUMES THAT
DETERMINE THEIR ADAPTABILITY FOR COVER PURPOSES

Characteristic	Degree ^a	Common examples
Texture	Fine	Kentucky bluegrass, bentgrass, red fescue
	Coarse	Smooth brome grass, reed canarygrass, timothy
Growth height	Short	Kentucky bluegrass, buffalograss, red fescue
	Medium	Redtop, perennial ryegrass
	Tall	Smooth brome grass, timothy, switchgrass
Growth habit	Bunch	Timothy, big bluestem, and dropseed, perennial ryegrass
	Sod former	Quackgrass, smooth brome grass, Kentucky bluegrass, switch grass
Reproduction	Seed	Red and alsike clover, sand dropseed, rye perennial ryegrass, field brome grass
	Vegetative	Prairie cordgrass, some bentgrasses
	Seed and vegetative	White clover, crownvetch, quackgrass, Kentucky bluegrass, smooth brome grass
Annual	Summer	Rabbit clover, oats, soybeans, corn, sorghum
	Winter	Rye, hair vetch, field brome grass
Perennials	Short-lived	Timothy, perennial ryegrass, red and white clover
	Long-lived	Birdsfoot, trefoil, crownvetch, Kentucky bluegrass, smooth brome grass
Maintenance	Difficult	Tall fescue, reed canarygrass, timothy, alfalfa
	Moderate	Kentucky bluegrass, smooth brome grass
	Easy	Crownvetch, white clover, birdsfoot trefoil, big bluestem
Shallow-rooted	Weak	Sand dropseed, crabgrass, foxtail, white clover
	Strong	Timothy, Kentucky bluegrass
Deep-rooted	Weak	Many weeds
	Strong	Big bluestem, switchgrass, alfalfa, reed canarygrass
Moisture	Dry	Sheep fescue, sand dropseed, smooth brome grass
	Moderate	Crested wheatgrass, red clover
	Wet	Reed canarygrass, bentgrass
Temperature	Hot	Lehman lovegrass, fourwing saltbush, ryegrass
	Moderate	Orchard grass, Kentucky bluegrass, white clover
	Cold	Alfalfa, hairy vetch, smooth brome grass, slender wheatgrass

^a Variety, specific characteristics, subcharacteristic, or favored condition.

From Lutton, R. J., U.S. Environmental Protection Agency, SW-867, 58, 1982.

more. The cell size varies with depth, but most often the waste ranges between 1.8 to 2.4 m in height where covered daily with 15 cm of soil. The depth of the trench also is dependent on the depth to groundwater. Thus, shallower depths accompany shallow groundwater levels. The bottom of the trench should slope to one end for leachate concentration, collection, and disposal when needed. The width of the trench sides depends on the kind of soil. For example, soils high in clay allow for thinner walls that slope less, than do coarse textured soils that require slopes to prevent "cave-in". The length of time the excavation remains open and the immediate weather conditions at each site also govern the thickness and slope of the walls between each trench. The trench method can be adopted to large or small operations.

Vertical mulching is closely related to trenching — generally it is designed for only narrow channels within the top 0.5 m of soil. Vertical mulching of nontoxic, nonhazardous, highly organic wastes and composted wastes has received favorable comment from agriculturalists,

Table 7
SELECTED GRASSES AND LEGUMES COMMONLY USED FOR REVEGETATION

Variety	Best seeding time	Seed density ^a (seeds/ft ²)	Important characteristics	Areas/conditions of adaptation
Grasses				
Redtop bentgrass	Fall	14	Strong, rhizomatous roots, perennial	Wet, acid soils, warm season
Smooth bromegrass	Spring	2.9	Long-lived perennial	Damp, cool summers, drought resistant
Field bromegrass	Spring	6.4	Annual, fibrous roots, winter rapid growth	Corbalt eastward
Kentucky bluegrass	Fall	50	Alkaline soils, rapid grower, perennial	North, humid U.S., south to Tennessee
Tall fescue	Fall	5.5	Slow to establish, long-lived perennial, good seeder	Widely adapted, damp soils
Meadow fescue	Fall	5.3	Smaller than tall, susceptible to leaf rust	Cool to warm regions, widely adapted
Orchard grass	Spring	12	More heat tolerant, but less cold resistant than smooth bromegrass or Kentucky bluegrass	Temperate U.S.
Annual ryegrass	Fall	5.6	Not winter hardy, poor dry land grass	Moist southern U.S.
Timothy	Fall	30	Shallow roots, bunch grass	Northern U.S., cool, humid areas
Reed canarygrass	Late summer	13	Tall, coarse, sod former, perennial, resists flooding and drought	Northern U.S., wet, cool areas
Legumes				
Alfalfa (many varieties)	Late summer	5.2	Good on alkaline loam, requires good management	Widely adapted
Birdsfoot trefoil	Spring	9.6	Good on infertile soils, tolerant to acid soils	Moist, temperate U.S.
Sweet clover	Spring	6	Good pioneer on nonacid soils	Widely adapted
Red clover	Early spring	6.3	Not drought resistant, tolerant to acid soils	Cool, moist areas
Alsike clover	Early spring	16	Similar to red clover	Cool, moist areas
Korean lespedeza	Early spring	5.2	Annual, widely adapted	Southern U.S.
Sericea lespedeza	Early spring	8	Perennial, tall erect plant, widely adapted	Southern U.S.

Table 7 (continued)
SELECTED GRASSES AND LEGUMES COMMONLY USED FOR REVEGETATION

Variety	Best seeding time	Seed density ^b (seeds/ft ²)	Important characteristics	Areas/conditions of adaptation
Hairy vetch	Fall	0.5	Winter annual, survives below 0°F, widely adapted	All of U.S.
White clover	Early fall	18	World-wide, many varieties, does well on moist, acid soils	All of U.S.
Crownvetch	Early fall	2.7	Perennial, creeping stems and rhizomes, acid tolerant	Northern U.S.

^a Taken from many sources.

^b Number of seeds per square foot when applied at 1 lb/acre (1.12 kg/ha).
Multiply by 10.76 to convert to seeds/m².

Lutton, R. J., U.S. Environmental Protection Agency, SW-867, 58, 1982.

turf green operators, and pasture specialists.¹⁰ The volume of disposal, however, is limited and the procedure is not well developed. Vertical mulching has been limited to problem soils and turf with water penetration and infiltration problems, compacted soils, excessively dense turf, and poor seedling establishment. Correction of the problems by vertical mulching is possible, but may not be long lasting. Vertical mulching has yet to become a significant vehicle for waste disposal.

Trench incorporation of organic wastes has received some attention as a feasible method for simultaneously disposing of sewage sludge and improving soil quality for agricultural crop production.¹¹ The method appears to be quite well adapted for dewatered (20% solids), raw-limed sludges. There is no reason trench incorporation procedures as developed by Walker cannot be favorable for widespread application of other municipal organic waste mixtures that are low in nitrogen. The procedure involves placing sewage sludge or some other suitable organic waste or composted waste in 60-cm-wide trenches of different depths and spacings. For example, dewatered sludge application rates of 800 and 1200 t/ha dry solids, respectively, were applied in trenches 60 cm wide by 60 cm deep by 60 cm apart and 60 cm wide by 120 cm deep by 120 cm apart. Results from this study were favorable for the waste material used.

IV. ENCAPSULATION

Encapsulation disposal is a burial process by which hazardous wastes are physically enclosed in a modified soil or synthetic encasement material to facilitate environmentally sound transport, storage, and/or disposal. The cost limits the use of encapsulation procedures to unusually toxic and hazardous nature that cannot be managed by the usual sanitary landfill-type burials.

Encapsulation techniques allow for waste constituent containment on several levels .

1. Wastes can be placed unaltered in a containment vessel.
2. On a smaller scale, wastes are mixed with synthetic material that encapsulate or coat the particles or grains to form a capsule by a technique called microencapsulation.
3. Wastes can be mixed with a binder that bonds the particles together without necessarily coating each granule.
4. Waste can be encapsulated by the production of new, inert, insoluble crystal lattices that bind the toxic elements into a durable, solid material.
5. Wastes can be embedded in concrete or pozzolan concrete.

Long-term, large-scale experiments are necessary before encapsulation techniques with land-fill disposal can be recommended with the confidence that no environmental degradation will occur over long periods of time.¹²⁻¹⁵

REFERENCES

1. **Andersen, J. R. and Dornbush, J. N.**, Influence of sanitary landfill on ground water quality, *J. Am. Waterworks Assoc.*, 59, 457, 1967.
2. JRB Associates, Inc., Remedial Action for Waste Disposal Sites: A Decision Making Guide and Technical Handbook, U.S. EPA-625/6-82-006, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1982, 497.
3. U.S. Army Engineers Waterways Experiment Station, Environmental Effects Laboratory, Chemical and Physical Effects of Municipal Landfills on Underlying Soil and Groundwater, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1978, 1.

4. **Fuller, W. H.**, Soil modification to minimize movement of pollutants from solid waste operations, *Crit. Rev. Environ. Control*, 9, 213, 1980.
5. **Brunner, D. R. and Keller, D. J.**, Sanitary Design and Operation, Solid Waste Management Series, SW-65ts, U.S. Environmental Protection Agency, Washington, D.C., 1972, 59.
6. **Fields, T. and Lindsey, A. W.**, Landfill Disposal of Hazardous Wastes: A Review of Literature and Known Approaches, U.S. EPA Rep., SW-165, U.S. Environmental Protection Agency, Cincinnati, Ohio, 36, 1975.
7. **Haxo, H. E.**, Assessing synthetic and admixed materials for lining landfills, in Gas and Leachate from Landfills — Formation, Collection and Treatment, U.S. EPA-600/9-76-004, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1976, 130.
8. **Lutton, R. J., Regan, G. L., and Jones, L. W.**, Design and Construction of Covers for Solid Waste Landfills, U.S. EPA-600/2-79-165, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1979, 249.
9. **Plehn, S. W.**, Draft Environmental Impact Statement, on the Proposed Guidelines for the Landfill Disposal of Solid Waste, OSW, Draft. U.S. Environmental Protection Agency, Washington, D.C., 1979, 186.
10. **Byrne, T. G., Davis, W. B., Booker, L. J., and Werenfels, L. F.**, Verticle mulching for improvement of old golf greens, *Calif. Agric.*, 19, 12, 1965.
11. **Walker, J. M.**, Trench incorporation of sewage sludge, in Proc. Natl. Conf. on Municipal Sludge Management, Pittsburgh, 1974, 1.
12. Waterways Experiment Station, Physical Properties and Leach Testing of Solidified/Stabilized Industrial Wastes, U.S. EPA-600/S2-82-099, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1982, 3 (Project Summary, 1983).
13. U.S. Department of Agriculture, Soil Conservation Service, Hydrology, SCS National Engineering Handbook, Sect. 4, U.S. Department of Agriculture, Washington, D.C., 1972, chap. 4.
14. **Fenn, D. G., Hanley, K. J., and De Geare, T. V.**, Use of Water Balance Method for Predicting Leachate Generation from Solid Waste Disposal Sites, Rep. No. EPA SW-168, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1975, 1.
15. **Loehr, R. C., Jewell, W. J., Novak, J. D., Clarkson, W. W., and Friedman, G. S.**, *Land Application of Wastes*, Vol. 1, Environmental Engineering Series, Van Nostrand Reinhold, 1979.
16. **Blanchet, M. S.**, Treatment and utilization of land fill gas: Mountain View Project Feasibility Study, U.S. Environmental Protection Agency, OSW, SW-583, 115, 1977.
17. **Lutton, R. J.**, Evaluating cover systems for solids and hazardous waste, U.S. Environmental Protection Agency, SW-867, 58, 1982.

Chapter 2

SOIL LINERS FOR LANDFILLS, IMPOUNDMENTS, AND PONDS

I. RATIONALE AND SCOPE

Soils (loams, clays, and clayey soils), soil cements, and crushed limestone remain as prime natural barrier or liner materials that can effectively influence retention of many pollutants of aqueous waste streams and leachates. Liners are used in waste disposal sites to prevent potential pollutant constituents from moving from the site and contaminating the surface and underground waters and entering the food chain.¹ Natural liners are installed or molded from existing soil to:

- Impede the flow rate of the pollutant and pollutant vehicle from the point of deposit. Yet, they must leak to prevent large volumes of leachates from accumulating. The purpose, however, is still to leak only acceptable quality water while retaining the potential pollutants in the disposal site.
- Attenuate, absorb, and degrade suspended and dissolved pollutant constituents to lower their concentration and toxicity to acceptable levels.

When wastes in any form are deposited on the soil surface or in the subsoil as burials, impoundments, or ponds and the soil is not completely impermeable, then the underlying groundwater may be contaminated by leachate constituents if these are not adequately retained by the soil that lays between the waste and groundwater. The widespread, ready availability of fine-textured soils is a great advantage, when soil is to be the liner material. Site selection procedures, therefore, must place liner-quality soil high on the list of priorities. Liner-quality soil is native material at or near the waste-disposal site and which can be properly homogenized, remolded, and/or compacted to provide a layer of low permeability to liquids. Liner soils may be needed to collect and direct gas flow. In such cases the liner must be porous, yet provide a firm layer or channel. Sands and gravels are preferred as liner⁵ for gas channels.

The design of the liner and its thickness not only depend on the properties of the soil, but also the specific site. Accordingly, if environmental conditions have been fully analyzed and understood, and the design follows the dictates of the environment and waste fluids, failure should not occur.² The characteristics of the three main components of the waste disposal environment (the soil, the leachate, and the pollutant) control the rate of movement of the pollutant through soil liners. Certain specific characteristics of soils and dilute aqueous leachates and their interactions for pollutant attenuation, particularly heavy metals, have been identified.¹ The evaluation of crushed limestone as a liner to limit metal movement from wastes placed on or in the soil also has been evaluated.^{1,3}

Recent research with soils and divergent waste streams has helped to identify certain physical behaviors and chemical reactions that must be considered if disposal operations are to be successful in minimizing environmental contamination and maximize suitable disposal site identification.^{4,5} At an ideal disposal site, the manipulation of the soil should limit potential pollutant movement sufficiently to prevent water and food chain contamination. However, even with an ideal site, the use of liners of disturbed soil may be needed. Since all soil landfills eventually leak water, the object is to reduce the associated pollutants of the leachates to acceptable levels by prudent soil manipulation. In the effective planning for liner and cover utilization, certain information about the soil should be evaluated before declaring a disposal site acceptable:

1. Depth of soil
2. Properties of soil (physical and chemical)
3. Properties of waste fluid
4. Properties of toxic and hazardous pollutants involved
5. Peculiarities of the liner selected and its reaction with the waste fluid components and surrounding environment
6. Site environment (climate, temperature, vegetation, water table, topography, hydrogeology, and aquifer location)
7. The functions to be performed by the soils at the site and list according to priority as related to ability to restrict pollutant movement from the place of deposit
8. Capacity of the soils to perform the functions required for liner material as indicated through soil tests

II. SOIL PROPERTIES AFFECTING ATTENUATION

Soils in their natural state vary widely in physical, chemical, and geological properties making evaluation of pollutant migration difficult and excessively time consuming. Thus, seldom is it possible to locate a disposal facility where soils are completely suited to carry out all of the necessary functions of liners as gas channels, collectors, intermediate and final cover, vegetative support, and blocking barriers. The limitations of the site soil, however, may be circumvented, in part at least, by adopting certain manipulation procedures. For example, compaction to different densities can improve the soil for different functions. Adjusting the thickness of the soil layers, also, assumes a practical innovative procedure to meet the required function. Furthermore, where a single soil cannot serve the design functions, other special procedures may be initiated, such as layering with different soil textures, or other materials, or the inclusion of nonsoil materials. Soil also has advantages as backup support and absorption barrier placed both over and under plastic liners.²

Critical information for screening soils as acceptable liner material and eventually for developing pollutant migration predictions must first be obtained by soil analyses.⁶⁻⁸

1. Physical analyses
 - Particle size distribution (over 2 mm diameter, under 2 mm diameter — USDA sand, silt, and <2 μm clay)
 - Bulk density
 - Soil particle surface area
2. Chemical analyses
 - Cation exchange capacity
 - Organic matter or total organic carbon
 - pH
 - Lime, gypsum, manganese consolidations and indurations
 - Hydrous oxides of iron
3. Profile analyses
 - Depth of soil layer to parent material
 - Texture changes with depth
 - Restriction layers — iron pans, clay pans, lime, etc.
 - Depth to bed rock
 - Depth to ground water

Useful data for screening and predictive purposes can be obtained through the development of breakthrough curves using homogeneous columns of site soil (or proposed liner soil) and

Table 1
COEFFICIENTS OF DETERMINATION (r^2) FOR EACH
ELEMENT ON DATA FROM TEN SOILS REPRESENTING
SEVEN OF THE TEN SOIL ORDERS

	Ions ^a							
	Cd	Be	Zn	Ni	Cr	As	Se	V
Clay, surface area, free iron oxides	0.93 ^b	0.87 ^b	0.88 ^b	0.82 ^b	0.56	0.78 ^c	0.57	0.75 ^c
Clay, surface area, free iron oxides, pH	0.94 ^b	0.91 ^b	0.93 ^b	0.86 ^c	0.83 ^c	0.78 ^c	0.84 ^c	0.75 ^c

^a Order does not imply level of significance.

^b Significant at 0.01 level.

^c Significant at 0.05 level.

From Korte, N. E., Skopp, J., Fuller, W. H., Niebla, E. E., and Alesii, B. A., *Soil Sci.*, 122, 356, 1976. With permission.

proposed leachate (or close facsimile or solvent). The soil-column technique is described in Chapter 4. Specific mechanics of the soil-column techniques vary with the type of fluid system involved. Field tests as verification of soil-column information are an important feature for preliminary screening of wastes to be put onto land.

The results of such tests indicate a significant correlation between (a) soil clay content, (b) particle surface area, (c) "free" iron content, and (d) pH and retention of heavy metals as pollutants (Table 1). The results are found by using the type of experiments described in Chapter 4 and by using stepwise multiple correlation. In these specific experiments, the lack of strong dominance of any single clay mineral in the $<2\text{-}\mu\text{m}$ size range, the type of clay mineral (montmorillonite-like, mica-like, or kaolin-like) did not improve the coefficient of determination r . It is shown that an equation utilizing the first three variables (i.e., percentage total clay and free iron oxide, and surface area) may be useful to predict the amount of absorbed heavy metals by the soils. Manganese was not found to be a significant variable because of its high cross correlation with free iron oxide ($r = 0.98$). Estimation of chromium (Cr) and selenium (Se) was significantly improved by the inclusion of pH as a fourth soil property. Inclusion of the cation exchange capacity (CEC) did not significantly improve the ability to predict the adsorption of these trace elements. Some soils were from arid lands where free lime may have interfered with the CEC evaluation.

Using these soil property data, we can rank heavy metal mobility with the different national representative soils.⁴ This ranking should not be considered as universal. The relative mobility of the heavy metals in dilute MSW landfill leachate was $\text{Hg} > \text{Ni} = \text{Cd} = \text{Zn} > \text{Be} > \text{Pb} = \text{Cu}$. The relative mobility of the anions tested was $\text{Cr} > \text{As} > \text{V} > \text{Se}$. The attenuation of the metals naturally separate into cations and anions. It is evident that no one single soil property can be used to rank the soils for retention properties as liner material. Copper and lead were the least mobile, but mercury the most. Those soils highest in clay retained heavy metals to a much greater extent than those low in clay. Sand was negatively correlated with attenuation. The hydrous oxides exert an increasing attenuation effect on the anions relative to soil texture as compared with the cations.⁹ The metal elements selenium (Se), vanadium (V), arsenic (As), and chromium (CrVI) were present in the municipal landfill leachates as anions.

III. LINERS

A. Concepts of Liners

The way the liner is used to modify the specific environment is related to the specific nature of the hazardous or toxic components in the waste and determines the efficiency and effectiveness of pollution control. For example, land disposal of hazardous waste from most industrial sources requires greater attention to selection, design, and management than would normally be required with leachates from municipal and other dilute aqueous wastes. Since liners are used primarily to prevent the potential pollutant in the waste from leaving the disposal site and entering the surface water, groundwater, or food chain directly, pollution abatement may be accomplished in several ways:

1. Restrict flow from leaving the disposal site as completely as possible. Liners in this category must be constructed of materials that provide impermeable or very low permeable barriers with provision for leachate and/or gas collection.
2. Do not completely restrict all flow of fluids carrying the pollutant from leaving the disposal site. Liners in this category must retain (absorb, adsorb, precipitate, and/or degrade) the pollutant(s) with provision for leakages of reduced pollutant concentration that will meet the U.S. EPA regulations of groundwater recharge.
3. In the case of gases, the soil may need only to function as channels and collection voids.

Several technologies may be suggested for soil and clay liners as follows:

1. For sludges containing valuable metal concentrations, burial of the waste in a separate and secure landfill site located in clay loam soil or lined with clay loam may be desirable so that leachate migration is retarded and metal pollutant concentrations in the leachates are retained. The dewatered sludge then can be mined at a later date and the metals recovered in a more cost-effective program. A good example of this actually occurred with an electronic industry shop waste in a desert area where evaporation was high and retention and concentration of the precious metals in the soil high.
2. Surrounding the isolated chemical sludge with a chemical liner (lime, hydrous oxides of iron or aluminum) to ensure an alkaline environment of the wastes and finally chemically removing the pollutants from the leachate has merit.

Concepts of liner technology most often center around that of impermeable barriers which prevents polluting leachates from movement beyond the site or from making contact between groundwater and the wastes constituents. Unfortunately, most impermeable liners have a limited life span. Furthermore, the impermeable liner creates a basin-effect which traps and holds leachates. Continued leachate accumulations, fed by rainfall, either escape by undesirable overflow or must be emptied periodically and treated before final disposal.

Soils may function as liners in several favorable ways. Clay soils, when properly compacted, can act essentially as an impermeable layer. By the time the liner begins to leak significantly, the solubility of the pollutants often is sufficiently stabilized to withstand liquid movement. Loams and loamy soils less permeable than clays can be compacted and layered at different thicknesses to permit slow release of leachate in small quantities and at low concentration of polluting constituents to provide some escape without jeopardizing underground water quality.

A classification of liners is provided in Table 2 as developed for the U.S. EPA by Matrecon, Inc.² to provide some degree of orientation. Since most natural soils are not homogeneous, heterogeneous features specific to the site must be considered when applying the models

Table 2
CLASSIFICATION OF LINERS FOR WASTE
DISPOSAL FACILITIES

- A. By construction:
 - Onsite construction:
 - Raw materials brought to site and liner constructed on site
 - Compacted soil
 - Mixed on site or brought to site mixed
 - Sprayed-on liner
 - Prefabricated:
 - Drop-in polymeric membrane liner
 - Partially prefabricated:
 - Panels brought to site and assembled on prepared site
- B. By structure:
 - Rigid (some with structural strength):
 - Soil
 - Soil cement
 - Semirigid
 - Asphalt concrete
 - Flexible (no structural strength)
 - Polymeric membranes
 - Sprayed-on membranes
- C. By materials and method of application:
 - Compacted soils and clays
 - Admixes, e.g., asphalt concrete, soil cement
 - Polymeric membranes, e.g., rubber and plastic sheetings
 - Sprayed-on linings
 - Soil sealants
 - Chemisorptive liners

From Matrecon, Inc., *Lining of Waste Impoundments and Disposal Facilities*, EPA SW-870, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1980, 32.

and equations developed from homogeneous soils. Evaluation of the heterogeneous nature of soil must depend on the experience and personal judgment of a soil scientist. As empirical as this may seem, it is necessary since almost all waste disposal will be involved with the natural soil whether or not liners are used. If the heterogeneity of the natural soil is excessive to the point of making the site unsuited to disposal, soil modification liners and a special synthetic lining becomes necessary. Some sites have such shallow soils or are so heterogeneous as to be wholly unacceptable.^{1,4,7,10}

Modified soils are classified into five major groups for convenience of this discussion:

- Compacted only
- Salt-expanded
- Cemented
- Sealed
- Limestone fortified

B. Compacted Soil

Compacting the soil with heavy equipment such as rollers, sheepfoot, and multiple tires causes volume changes that are assumed to alter the density and flow properties of the soil liner. Volume changes under natural conditions take place when the soil loses water and when the soil can overcome the load restriction of the overburden.² The extent of volume change, for a selected change in water content, depends mostly on:

1. Clay mineral type (e.g., montmorillonites, micas, kaolinites, sesquioxides, etc.)
2. Particle structures (e.g., arrangement of soil particles)
3. Texture or soil particle size distribution (e.g., sand, silt, clay)
4. Surface area per unit weight
5. Moisture content at time of compaction
6. Kind of adsorbed cations

Some relationships of compaction have been well established. It can increase the maximum density and decrease the optimum moisture content. Because tests with soils of high clay content result in variable relationships, quality control in the field requires considerably more attention for clay soils.

Volumes can change after mechanical compaction for reasons as follows:²

“(a) Upon removal of compacting implements, the stresses applied will relax with the result that the soil will tend to rebound to a higher void ratio. Even where this process takes place without loss of water into the atmosphere, the magnitude of negative pore water pressure will, in general, increase and the expansion process should tend toward a larger void ratio, the value of which depends on soil elastic properties, the magnitude and persistence of stresses applied during compaction, the overburden of the point-soil element considered, the void ratio achieved at the end of compaction, etc. If superimposed on this, there is also a net loss of water in evaporation, then there will be a simultaneous reduction of the original volume of the soil. The reduction in volume can result in the formation of microfissures which, in turn, can greatly alter the flow properties of the soil liner while in service. (b) The compaction of a soil material into a soil liner generates, at a given set of conditions, a certain characteristic structure with a corresponding void ratio and, if the internal structure of the soil is rigid, a certain set of flow properties. During compaction the equilibrium soil structure and void ratios achieved depend on the forces which oppose soil deformation, strongly correlated with the characteristic swelling pressure of the system, i.e., soil-matrix and soil-fluid compositions. Since the fluid composition during compaction is different from the composition during the service exposure, changes in swelling characteristics have to be expected, and a corresponding volume change of the soil liner can result if permitted by constraining stresses.”

Compaction of the soil for liner purposes accomplishes one main aim for pollutant retention, namely, reduction in permeability. According to the modified AASHTO compaction test procedure,¹¹ compaction density relationships depend on a number of critical specifications to provide a successful soil liner for pollutant containment. Briefly, they are

1. Natural clay content — 25 to 30%
2. Compaction in a range of optimum, or slightly above optimum, moisture contents
3. “Stage-compaction” or correct thickness of the rolled layer to provide a liner with a low permeability¹²
4. Definition of the desired relative density or percentage compaction stated as “percentage of the laboratory maximum density”
5. Compaction under a dispersed soil condition when possible

Compaction to the desired density or permeability is one of the real advantages of the clay in soils. However, only rarely can clayey disposal sites be found with sufficient homogeneity to lend themselves to pollution control without mechanical manipulation. Homogenization is essential to almost all site preparations and must become a required practice prior to compaction of the soil layer. Some examples of soil modification by mixing include

1. Mechanically stirring and mixing *in situ* at the bottom and along the sides of the excavation and packing to the desired density to establish permeability below 1×10^{-7} cm/s.
2. Returning some of the stockpiled clayey mixture from the excavation, to the disposal site to be replaced in a homogeneous liner of the desired thickness and compaction.

Should the soil at the site not contain 25 to 30% clay, clayey soil should be brought into the site from another suitable soil area.

3. Surrounding the wastes and containers of hazardous wastes with clay soil in cell-like structures so the soil material is interlayered throughout the disposal area as compacted homogeneous barriers.
4. Increasing the depth of soil where depths are shallow. This situation requires hauling suitable clayey soil to the site. Compacted liners of even low permeability need a minimum depth of 3 m to be effective pollutant barriers. Also, see Coates and Yu¹³ and Table 3 for a description of equipment and details of the methods of compaction.

C. Salt-Expanded Soil

Native soils having 22 to 35% clay ($<2\ \mu\text{m}$) by weight may be used for preparing salt-expanded liners impervious to aqueous solutions and for disposal ponds of certain industrial fluids. A salt-expanded liner of 0.5 to 1.0 m has proved effective for retaining runoff water collected for freshwater lagoons in the southwestern U.S.^{1,8} The procedure is to stockpile soil (having a minimum of 25% clay and 10 meq/100 g CEC) from the lake, pond, or lagoon excavation or imported to the site. The liner is laid down by "stage-compaction" of about 15 cm layers (lifts) at a time with sufficient rock salt (NaCl) applied to satisfy 25% of the CEC and at a moisture content of about 40% of its "normal field-water-holding" capacity. Other dispersing salts such as carbonates and phosphates are effective, but the economics may be less favorable. Phosphorus can be an unfavorable factor in eutrophication.

Compaction with heavy roller and sheepsfoot equipment may be necessary to achieve 98% of "percentage of laboratory maximum density". The liner should never be allowed to air dry without repacking because of shrinking and cracking. The most suitable soil materials contain the nonexpanding lattice clay minerals such as illite and kaolin. Bentonite or montmorillonite expanding-lattice-type clay shrink and swell and crack more readily than nonexpanding clays, particularly around the edges of the disposal ponds and impoundments where shorelines fluctuate and are subjected to repeated drying and wetting. Liner construction and thickness as well as kind to use depends wholly on the nature of the liquid to be retained. Therefore, each disposal must be reviewed independently and a liner program developed to satisfy the requirements of a specific disposal and local environmental conditions at the proposed site.

D. Soil Cements

Irrigation canals lined with soil cement have received favorable responses from users in the western states. The liners are prepared by compacting a mixture of Portland cement, water, and selected *in situ* soils. The resulting concrete has greater stability than natural soil, but is relatively low in strength compared with the usual concrete liner. We suggest soil cements in western states where relatively large water reservoirs are needed and the soil and water are neutral or near neutral, but the soil is too coarse to establish an impervious salt-expanded clay liner. The permeability differs with the particle size distribution of the soil. Fine textured soils (clays, clay loams) result in the lowest permeability according to studies of Stewart¹⁴ with a range averaging near $10^{-6}\ \text{cm s}^{-1}$ to $10^{-7}\ \text{cm s}^{-1}$. Permeabilities have been reduced by coating with sealants compatible with the fluid to be stored, evaporated, or transported. Soil textures most desirable for soil cements are recommended by the Bureau of Reclamation.^{15,16} Also see Stewart¹⁴ for details of preparation and application to liquid storage.

E. Soil Sealants

The object of sealants is to reduce the permeability of natural compacted soil by application of a variety of chemicals and latexes. Application methods vary from spraying, mixing

Table 3
COMPILATION OF SOIL COMPACTION EQUIPMENT AND METHODS

Requirements for compaction of 95 to 100% Standard Proctor, maximum density					
Equipment type	Applicability	Compacted lift thickness, in. (cm)	Passes or coverages	Dimensions and weight of equipment	
				Soil type	Foot contact area, in. ² (cm ²)
					Foot contact pressures, psi (MPa)
Sheepsfoot rollers	For fine-grained soils or dirty coarse-grained soils with more than 20% passing No. 200 mesh; not suitable for clean coarse-grained soils; particularly appropriate for compaction of impervious zone for earth dam or linings where bonding of lifts is important	6 (15)	4–6 passes for fine-grained soil; 6–8 passes for coarse-grained soil	Fine-grained soil PI > 30	5–12 (32–77)
				Fine-grained soil PI < 30	7–14 (45–90)
				Coarse-grained soil	10–14 (64–90)
					250–500 (17–34)
Rubber tire rollers	For clean, coarse-grained soils with 4–8% passing No. 200 mesh For fine-grained soils or well-graded, dirty coarse-grained soils with more than 8% passing No. 200 mesh	10 (25)	3–5		200–400 (1.4–2.8)
					150–250 (1.0–1.7)

Possible variations in equipment

For earth dam, highway, and airfield work, drum of 60-in. diameter (152 cm), loaded to 1.5–3 tons per lineal ft (43.7–87.5 kN per lineal m) of drum generally is used; for smaller projects, 40-in. diameter (101 cm) drum, loaded to 0.75 to 1.75 tons per lineal ft (21.9–43.7 kN per lineal m) of drum is used; foot contact pressure should be regulated so as to avoid shearing the soil on the third or fourth pass

Wide variety of rubber tire compaction equipment is available; for cohesive soils, light-wheel loads such as provided by wobble-wheel equipment, may be substituted for heavy-wheel load if lift thickness is decreased; for cohesionless soils, large-size tires are desirable to avoid shear and rutting

Efficient compaction of wet soils requires less contact pressures than the same soils at lower moisture contents

Tire inflation pressures of 60 to 80 psi (0.41–0.55 MPa) for clean granular material or base course and subgrade compaction; wheel load 18,000–25,000 lb (80–111 kN); tire inflation pressures in excess of 65 psi (0.45 MPa) for fine-grained soils of high plasticity; for uniform clean sands or silty fine sands, use large size tires with pressure of 40 to 50 psi (0.28–0.34 MPa)

Smooth wheel rollers	Appropriate for subgrade or base course compaction of well-graded sand-gravel mixtures May be used for fine-grained soils other than in earth dams; not suitable for clean well-graded sands or silty uniform sands	8—12 (20—30) 6—8 (15—20)	4 6 3-wheel roller for compaction of fine- grained soil; weights from 5—6 tons (40—53 kN) for materials of low plastic- ity to 10 tons (69 kN) for materials of high plasticity	3-wheel rollers obtainable in wide range of sizes; 2-wheel tandem rollers are available in the range of 1—20 tons (8.9—178 kN) weight; 3-axle tandem rollers are generally used in the range of 10—20 tons (89—178 kN) weight; very heavy rollers are used for proof rolling of subgrade or base course
Vibrating base- plate compactors	For coarse-grained soils with less than about 12% passing No. 200 Mesh; best suited for materials with 4—8% passing No. 200 mesh, placed thoroughly wet	8—10 (20—25)	3 Single pads or plates should weigh no less than 200 lb (0.89 kN); may be used in tandem where working space is available; for clean coarse-grained soil, vibration frequency should be no less than 1,600 cycles per minute	Vibrating pads or plates are available, hand-propelled or self-propelled, single or in gangs, with width of coverage from 1.5—15 ft (0.45—4.57 m); various types of vibrating- drum equipment should be considered for compaction in large areas Tractor weight up to 60,000 lb
Crawler tractor	Best suited for coarse-grained soils with less than 4—8% passing No. 200 mesh, placed thoroughly wet	10—12 (25—30)	3—4 No smaller than D8 tractor with blade, 34,500 lb (153 kN) weight, for high compaction	
Power tamper or rammer	For difficult access, trench backfill; suitable for all inor- ganic soils	4—6 in. (10—15 cm) for silt or clay; 6 in. (15 cm) for coarse- graded soils	30 lb (0.13 kN) minimum weight; consid- erable range is tolerable, depending on materials and conditions	Weights up to 250 lb (1.11 kN); foot diameter 4—10 in. (1.57—3.93 cm).

From Coates, D. F. and Yu, Y. S., **Eds.**, Pit Slope Manual, Waste Embankments, CANMET Rep. T 1-1, Canada Center of Mineral and Energy Technology, Ottawa, Canada, 1978, 90.

Table 4
SELECTED REPRESENTATIONS OF SOIL SEALANTS

Sealant	Application	Remarks
Cationic asphalt emulsion	Farm ponds	Requires approximately 19,000 $\ell/4,047 \text{ m}^2$ (5,000 gal/acre) dispersed in water
Oil soluble polymers in diesel fuel	Fresh water	Injected beneath surface of water where seepage was occurring
Sodium tetraphosphate	Sulfite liquor storage	Dispersant distributed in 15.2-cm (6-in.) layer of soil at 2.3 kg/9 m^2 (5 lb/100 ft^2); careful compaction rendered soil impervious
Sodium carbonate	Canals	Wet-dry cycles disrupt water barrier; used 183 g (0.4 lb) of reagent/0.84 m^2 (yd^2) of soil
Lignin derivates gelled alum	Desalination by-product brine	1% lignin; cost \$3,400/4,047 m^2 (acre)
Carboxymethyl cellulose with alum	Desalination by-product brine	0.2% CMC; cost \$2,250/4,047 m^2 (acre)
Petroleum emulsions	Desalination by-product brine	4% additive; cost \$4,400/4,047 m^2 (acre)
Attapulgit clay	Desalination by-product	2% Zeogel; cost \$1,000/4,047 m^2 (acre)
Liquid elastomeric polymer	Fresh water	Patent discloses several compositions, including polyurethane elastomers

From Parks, C. F. and Rosene, R. B., Preventing Losses of Industrial and Fresh-Water from Pits, Ponds, Lakes, and Canals, Preprint No. EQC-64, American Institute of Mechanical Engineering, Environmental Quality Conf., 1971, 351.

inplace, and waterborne, to injection below soil surface. Numerous soil sealants are commercially available (Table 4). They may include monovalent cationic based salts (Na^+), powdered polymers which form gels, (extracted lignin), petroleum-based emulsions, and resinous polymer-diesel fuel substances.¹⁷

Soil sealants provide only temporary confinement of liquids that are limited mostly to water and dilute water solution. Moreover, they are thin, subject to microbial attack, and survive poorly under conditions of wetting and drying and/or freezing and thawing. Thus, they must be considered as temporary barriers. Like the soil liners, they permit leakage even though the rate may be slow.²

F. Limestone Liners

1. Crushed Limestone

Many of the same properties that influence heavy metal retention by soil material influence the effectiveness of crushed limestone liners.^{3,8,18,19} Limestone appears to be as effective with clays as with sandy soils (Table 5). For example, the effect of crushed limestone layered (2 cm) over six different reference soils on the retention of beryllium, cadmium, and iron from MSW landfill leachate is illustrated in Figures 1, 2, and 3, respectively.^{1,8} Because of the possibility of clogging, limestone is more effective when layered over a leaking or slowly permeable rather than an impermeable soil, although it can be used in both situations.

Crushed agricultural limestone varies in degree of effectiveness for minimizing migration of potential pollutants in aqueous leachates, depending on the way it is associated with soil as well as the kind of soil involved. Layering or lining the soil is preferred to mixing limestone with soil or solid waste. Mixing limestone with soil may result in soil stabilization or cementation that temporarily will inhibit the movement downward. At a later date, fixed channels form holes through which leachates can move into the natural soil and geological material without first having had much of an opportunity to react with the barrier material.

Furthermore, in humid climatic regions characterized by acid soils, mixing soil with

Table 5
RELATIVE EFFECT OF CRUSHED LIMESTONE LINER PLACED OVER SOIL ON THE RATE OF RETENTION
OF SOME ANION-FORMING METALS IN AQUEOUS LANDFILL LEACHATE

Metal	Pore volume displacement to achieve breakthrough ($c/c_o = 1$)											
	With limestone layer with soil						No limestone layer, soil only					
	Davidson c	Ava sicl	Anthony sl	Mohave sl	Kalkaska s	Wagram s	Davidson c	Ava sicl	Anthony sl	Mohave sl	Kalkaska s	Wagram s
As (pH 5.2)	110	59	96	140	88	90	21	22	22	20	18	12
Cr (pH 2.5)	35	42	85	88	86	65	10	15	15	10	10	6
Cr (pH 4.0)	48	49	125	144	111	109	12	21	39	25	17	15
Se (pH 5.2)	125	68	130	142	92	85	22	35	19	21	19	17
V (pH 5.2)	51	55	70	92	82	69	20	25	16	15	17	10

Fuller, W. H. and Artiola, J., Land Disposal of Hazardous Wastes, Shultz, D. W., Ed., Proc. 4th Annu. Res. Symp., San Antonio, EPA-600/9-78-061, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1978, 282.

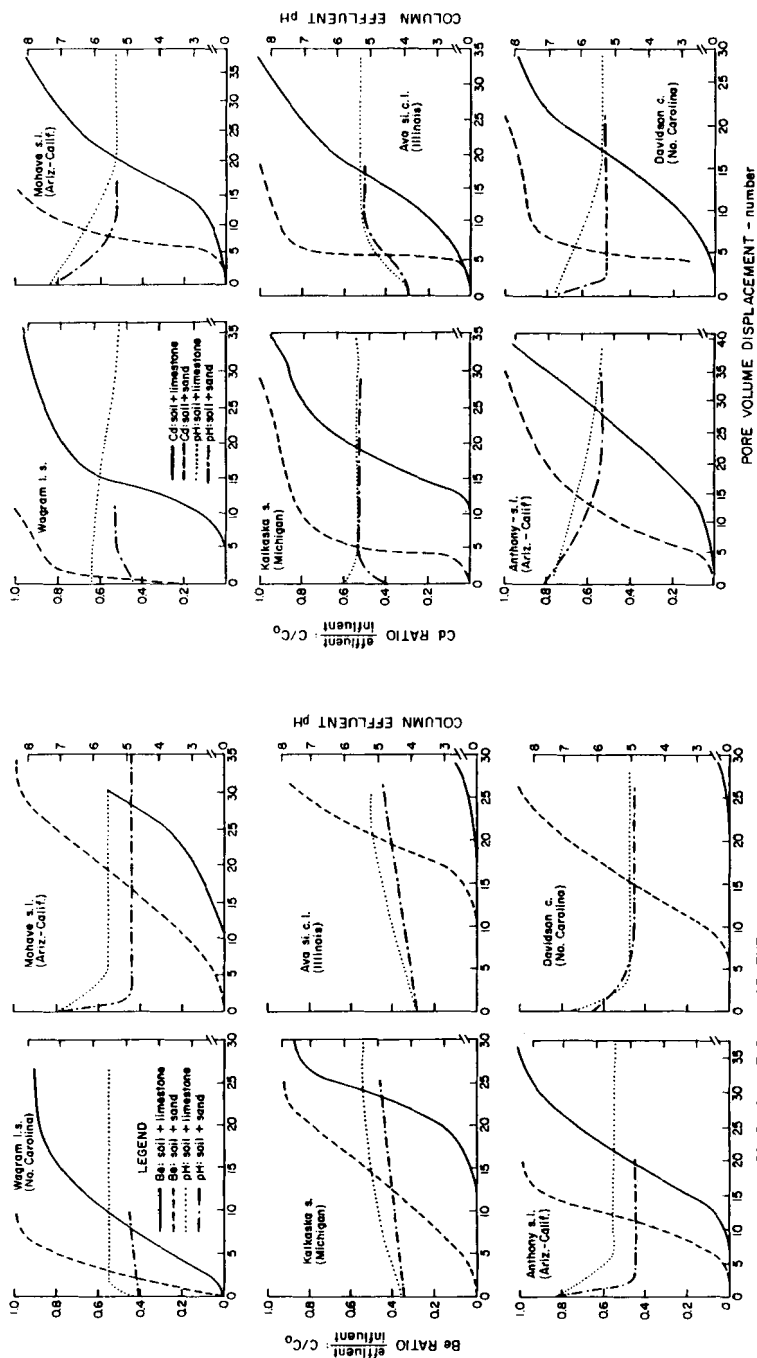


FIGURE 1. Relative migration rates of beryllium in MSW landfill leachate 1.5 years old and displaced through 6 different reference soils layered with and without 2 cm of crushed limestone. (From Artiola, J. and Fuller, W. H., *Soil Sci.*, 129, 167, 1980. With permission.)

FIGURE 2. Effect of crushed limestone layered (2 cm) over 6 different reference soils on the retention of cadmium from MSW landfill leachate. (From Artiola, J. and Fuller, W. H., *Soil Sci.*, 129, 167, 1980. With permission.)

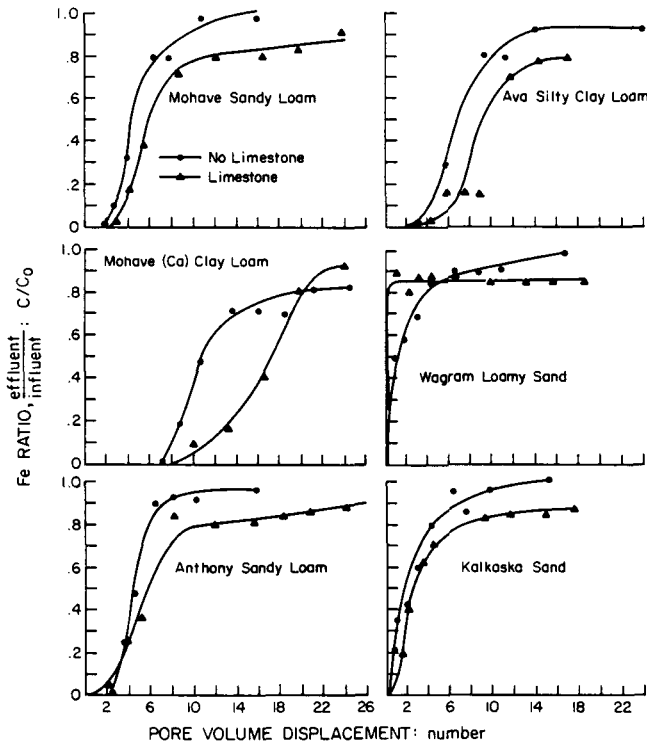


FIGURE 3. Effect of crushed limestone layered (2 cm) over 6 different reference soils on the retention of iron of MSW landfill leachate 2.5 years old. (From Artiola, J. and Fuller, W. H., *Soil Sci.*, 129, 167, 1980. With permission.)

limestone results in rapid disappearance and ineffective consumption of the limestone by the acid of the soil. Continued need for repeated application of limestone by agriculturalists to counteract soil acidity in plant nutrition is well known. In leachate pollutant control, the purpose of limestone is not necessarily to neutralize acidity of soil, but to react directly with potentially toxic constituents of the leachate before they enter the soil as well as raising the pH level of the leachate passing through which, in turn, lowers the solubility of most heavy metals.

The use of crushed limestone liners over soil rather than other methods of application is further supported by the finding that metal retention is greater when soil and limestone are layered together than the sum of attenuation achieved separately. Data in Table 6 provides evidence of this synergic effect. Adding crushed limestone to solid waste or to the generated leachate to aid in neutralizing the acid formed under anaerobic conditions seems to have little experimental or field support at present. Neutralizing the acid often results in biological production of more acid and often has been associated with retardation of biodegradation processes. However, the sludge or slurry created by the lime can cause plugging of the pores in the soil below the fill and may further impede the flow of the treated water downward out of the disposal basin as may be desired.

2. Leachate Relationships

One of the most important characteristics of aqueous leachate for influencing the rate of metal migration through limestone lined soil is pH. Any technique to reduce acidity of the leachate (by raising the pH) minimizes pollutant movement, enhances the effectiveness of the limestone, and lengthens its life.^{20,21}

Leachates high in acid, TOC, and soluble salts possess a greater limestone requirement than more dilute leachates.²² For this reason young (0 to 5 years) leachates consume limestone

Table 6
EFFECT OF LIMESTONE ALONE AND LIMESTONE
LAYERED OVER SOILS ON THE ATTENUATION OF
CHROMIUM IN MSW LANDFILL LEACHATE

Soil			Ratio of Cr in influent & effluent (c/c ₀)	PVD number when Cr concentration in effluent is at c/c ₀ , given in Column 4		
Series	Clay (%)	pH		Limestone alone	Soil alone	Soil and limestone
Davidson c	52	6.2	0.13	2	2	28
Ava s1cl	31	4.5	0.38	5	21	49
Anthony sl	15	7.8	1.00	57	39	125
Mohave sl	11	7.3	0.76	46	25	144
Kalkaska s	5	4.7	1.00	57	17	111
Wagram s	4	4.2	1.00	57	15	109

Note: Leachate had a pH value of 4.0, TOC of >3000, and Fe of 300 ppm.

From Fuller, W. H. and Artiola, J., Land Disposal of Hazardous Wastes, Shultz, D. W., Proc. 4th Annu. Res. Symp., San Antonio, EPA-600/9-78-061, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1978, 282.

more rapidly than older leachates. Of course, pollutant movement (including metals) is much more pronounced during this early stage of biodegradation and leachate generation. Thus, limestone is more effective at this stage. Utilization of limestone is directly proportional to the leachate acidity. Therefore, the greater the acidity, the greater the thickness of limestone required, because of dissolution loss. Certain industrial solutions and leachates high in toxic metals and/or acids will require additional individual study to determine the best method for lining with crushed limestone and the most suitable thickness and particle sizes. Again, limestone use should be tailored specifically for each waste stream. Those practical properties that influence the way crushed limestone itself contributes to effectiveness as a liner are listed for convenience:

- Particle size distribution
- Quality of limestone
- Thickness of limestone layer
- Extent of compaction

3. *Limestone Particle Size*

Particle size distribution of limestone within the range of the coarse sand to fine gravel appears to be best suited for layering over soil (Table 7). Fine, powdery limestone will cake, stabilize, and cause many problems with infiltration. Nor is coarse material (e.g., all gravel sizes) the most efficient size because of the limited surface areas available for leachate contact. A distribution of various particle sizes within the above ranges is suggested; caution should be taken to avoid excessive levels of fine and very coarse sizes, even within this range. Thick layers should include coarser ranges of material than thin layers.

4. *Limestone Quality*

The quality of limestone varies from source to source (Table 7). Dolomitic limestone (magnesium carbonate) is less effective than calcium carbonate limestone. Magnesium car-

Table 7
PARTICLE SIZE DISTRIBUTION OF AGRICULTURAL LIMESTONE FROM KENTUCKY SOURCES¹⁹

Sieve size classes			Limestone source — % of size separation		
ϕ	mm	USDA	Lexington	Cedar Bluff	Gibsonburg
-2.5 to -2.0	-5.66	Gravel	0.9	0	0
-2.0 to -1.5	5.66—2.80		17.3	5.1	0
-1.5 to -1.0	2.8—2.00	—	13.2	4.4	0
-1 to -0.5	2.00—1.40	Very coarse sand	15.2	6.8	0
-0.5 to 0	1.40—1.00	—	11.4	7.8	0
0 to 0.5	1.00—0.71	Coarse sand	10.2	8.3	0
0.5 to 1.0	0.71—0.50	—	7.5	9.4	0
1.0 to 1.5	0.50—0.355	Medium sand	8.3	12.5	0.3
1.5 to 2.0	0.355—0.250	—	6.0	10.2	0.4
2.0 to 2.5	0.250—0.180	Fine sand	3.0	6.7	1.4
2.5 to 3.0	0.180—0.125	—	2.4	6.3	6.8
3.0 to 3.5	0.125—0.090	Very fine sand	1.5	4.8	13.3
3.5 to 4.0	0.090—0.63		1.0	6.0	13.5
	0.06—0.050	—	0.8	1.9	24.7
	<0.050	Silt + clay	1.2	9.9	39.5

bonate reacts more slowly, and often incompletely, with cold acids of the leachate. However, it may form slick, bulky colloids with organic and inorganic constituents that clog and seal the disposal lining, encouraging channel formations. Silicates associated with limestone may also reduce infiltration rates. Diluents such as quartz sand and gypsum sand are less objectionable. High quality limestone (CaCO_3) should be used since it is most effective for the precipitation of pollutants.

5. Limestone Thickness

The thickness of the limestone liner to be used depends on several factors and a good deal of judgment. Leachate composition varies widely and quantitative relations for leachate quality, liner thickness, and contaminant retention are generally poorly defined. Hydrous oxides of Fe are classical products of metal/constituent reactions. Carbonates and sulfates of low solubility form as well as organic slimes. Such coatings minimize penetration of acids and other constituents to the actual limestone surfaces. Eventually, the limestone outer surfaces becomes almost completely unreactive to leachate constituents. The extent of this inactivation, however, is not fully known, nor is there any known method for overcoming this effect under the usual conditions of landfill liner practice.

G. Hydrous Oxides of Iron

Preliminary research indicates that even a thin layer (<1 mm) of hydrous oxide of iron reduces the migration rate of certain heavy and trace metals (Figure 4).¹ A liner was constituted of common rust taken from weathered steel and ground to pass a 20-mesh screen. Iron was not dissolved from the oxides by the leachate. Where FeSO_4 was used by spraying an aqueous solution onto the surface of soil used in columns, soluble Fe was identified in the effluent despite the retention effect it had on certain heavy metals. Because of this leaking effect, techniques for practical use of ferrous-sulfate-mine-waste for liner purposes are not recommended at this time.

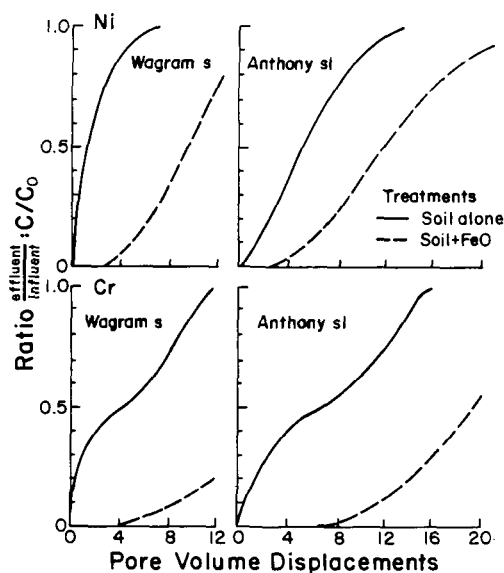


FIGURE 4. Effect of the hydrous oxides of iron precipitated on Anthony s l and Wagram s on retention of Cr VI and Ni of MSW landfill leachate 2.5 years old. (From Fuller, W. H., *Liners of Natural Porous Materials to Minimize Pollutant Migration*, EPA-600/S2-81-122, U.S. Environmental Protection Agency, MERL, Natl. Tech. Info. Serv., Springfield, Va., 1981, 73.)

IV. LINERS FOR BURIALS

A. Landfills

1. Attenuation of Pollutants

Soil liners attenuate pollutants to different extents by lowering the maximum concentration as the fluid (aqueous leachates of landfills) passes through the material. The greater the distance (or time) of travel, the lower is the expected concentration. However, there is more to attenuation than the definition may imply as was elaborated in the earlier chapters. As explained by Haxo of Matrecon, Inc., attenuation implies that a soil liner cannot be an "absolute" liner. Figure 5 illustrates this point. Certain assumptions were made:

1. The degree of contamination is defined as the amount of polluting species passing through a unit area per unit time, e.g., grams per square meter per day ($\text{g}/\text{m}^2/\text{day}$).
2. The rate of contamination is evaluated in all cases at a depth L from the waste interface. The depth L is also taken as the thickness of the liners in cases B through E, inclusive.
3. The permeability of the liners in Cases B through E, inclusive, is assumed to be the same.
4. The permeability of the native soil is assumed to be greater than that of the clayey soil liners.
5. The absorptive capacity for the polluting species in Case C is less than the corresponding capacity in Case D.
6. The absorptive capacity of the liner in Case E is greater than the total mass loading of polluting species of the single load situation.

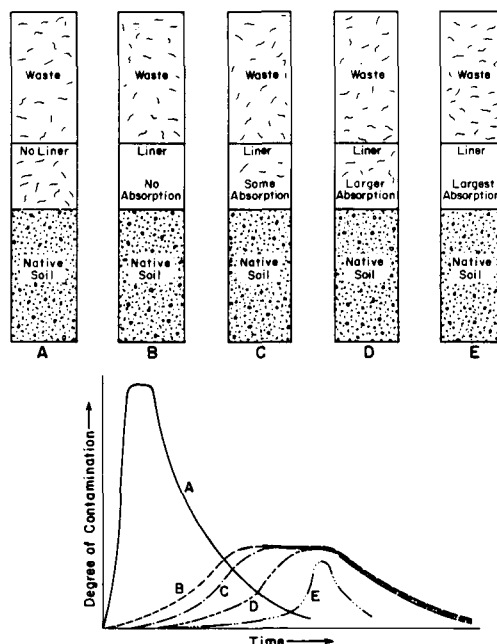


FIGURE 5. Attenuation of polluting species by soil liners of different absorptive capacities and schematic representation liner situations and the rate of contamination of soil liners shown above at the depths equal to the thickness of the liners. (From Matrecon, Inc., Lining of Waste Impoundments and Disposal Facilities, EPA SW-870, U.S. Environmental Protection Agency, OWWM, Cincinnati, Ohio, 1980, 385, 38.)

7. The single unit load situation is defined as a set, finite amount of polluting species at a given hydraulic gradient which, over time, will approach zero as the polluting species passes through the soil and/or liner and is not replenished.
8. The constant, continuous waste loading is defined as the maintenance of a given constant concentration of polluting species at a given hydraulic gradient over time. This implies replenishment of the polluting species in the waste.
9. The analysis assumes saturated flow.
10. The analysis assumes that the waste does not damage the liner or its structural integrity.

Considering Figure 5, case A has the highest flux of contaminants within the shortest period of time. This single unit loading is represented by curve A as a short plateau that declines rapidly as the amount of pollutant remaining decreases. In case B, where the loading is maintained at a constant rate, continuously, the plateau does not drop off, but remains at its peak level. The liner in B functions wholly to impede flow by reduced permeability. Case A differs from B in intensity of contamination since the capacity for contamination is the same and no absorption takes place. The flat plateau of the curves must represent dissolution/precipitation reactions of the effluent. The permeability differential lowers the intensity factor, leaving the capacity of the contamination unchanged. Only a retardation effect remains.

Where liner absorption occurs, as in cases C and D, the maximum rate of contamination is delayed; therefore, at any time prior to attaining the "maximum-rate-plateau", the difference in rate curves represents the magnitude of absorptive capacity of each liner type. Haxo² defines this absorptive capacity as the altering of the chemical composition of the waste leachate with respect to the polluting species "such that the species is irreversibly retained by the liner".

If absorption is so dominant that only a small amount of leakage takes place on a single loading situation, the case E curve prevails (Figure 5). With continuous constant loading, the case E plateau will eventually approach that of cases B, C, and D. No plateau will appear if the liner retains all of the pollutant from the leachate.

2. *Waste Characteristics*

Design of the liners to use on landfills is predicated to a realistic extent on the characteristics of wastes and the quality and quantity of leachate generated. Some of the usual waste characteristics that should be identified include

- Chemical and physical composition
- Moisture content
- Quantity and quality of the leachate expected to be generated
- Thickness
- Unit weight (in place)
- Compaction prior to disposal
- Hazardous components
- Gas-forming potential

The waste fluids assume primary importance in pollution containment of landfills and other burials. The waste fluids (leachates, waste streams, solvents, and gases) become the transport system of land burials since they carry soluble constituents, certain colloids, and macromolecules through the voids of the porous media. Solubility and solubilization of the waste constituents in the landfills, therefore, contribute to pollutant movement and may challenge the integrity of the liner. The great variety of waste fluids of aqueous solutions, acids, alkalines, organic solvents capable of carrying a host of inorganic (e.g., heavy metals, salts), organics (POB, pesticides, TCE, etc.), microorganisms (disease bacteria, virus, and other health hazardous organisms) adds to this burden of barrier liners and the difficulty in predicting liner requirements. Even within a single source of transport liquid, such as municipal solid waste (MSW) landfill leachate, the chemical composition varies²³ (Table 8). Certain common constituents, however, are common to all MSW landfill disposals. As a consequence, it is convenient to analyze these common constituents as evidence of pollution contamination of groundwaters (Table 9).²⁴ The greatest source of variation in potentially hazardous pollutants in MSW landfill leachates originates from industrial disposals along with the solid waste. Industrial incorporations vary in extent from location to location and with the size of the metropolitan area involved in landfill disposal. Generally, the larger and older the city, the greater the tendency to mix industrial and municipal wastes.

3. *MSW Leachate Effects Upon Liners*

The behavior of MSW leachates in soil is beyond complete chemical, physical, and biological identification.²⁵ Yet the rate of movement of certain potential pollutants (e.g., heavy metals) found in MSW landfill leachates can be correlated with some measurable broad parameters of both leachate and soil. For example, with MSW landfill leachates, the total organic carbon compound (TOC) concentration, fluid pH, and concentration of soluble common salts and some naturally occurring heavy metals, notably iron, statistically correlate highly with most heavy metal movement through soils (Figure 6). Usually the lower the pH level and the higher the concentration of other constituents, the more rapid is the movement of the potential pollutants through the soil. Therefore, the behavior of MSW landfill leachate with respect to its influence on retention of heavy metals by soils and soil liners is not the same generated from freshly deposited waste as from that deposited longer. Age of leachates must be taken into account in liner designs. Aqueous leachates from landfills

Table 8
RANGE OF CONSTITUENTS DETECTED IN THE NATURAL LEACHATE
GENERATED FROM MUNICIPAL SOLID WASTE (mg/ℓ)^a

Constituent	Leachate I range		Leachate II range		Leachate III range	
	Overall	Used in study	Overall	Used in study	Overall	Used in study
Time span	11/29/73	1/15/79	10/23/75	1/15/79	10/23/75	1/15/79
COD	50—500	100—200	—	—	50—200	200
TOC	123—1,155	200—900	1,400—25,000	700—10,000	250—1,000	250
pH	4.5—7.0	6.4—6.8	3.8—7.0	5.4	5.4—6.2	6.2
EC (mmhos/cm)	1.2—4.2	2.6—3.5	5—17	9.0—11.5	1.9—2.5	1.9
TDS	768—2,680	1,660—2,240	3,200—11,000	5,000—7,000	1,200—1,600	1,220
Total P	0.8—7.9	2.0—4.0	2—33	12	2—20	nd
NH ₄ -N	70—190	125—150	nd	nd	nd	nd
Cl	93—350	~3,900	300—600	nd	150	150
Ca	90—275	160—225	100—1,750	200—1,000	150—500	730
Mg	14—106	25—60	40—450	60—360	85—180	85
Na	55—150	55—150	135—750	150—640	200—300	193
K	108—2,050	850—950	500—1,600	600—700	40—400	40
Si	12—31	20—25	22—44	32—33	25—28	15
Cd	<0.02	<0.02	<0.02—0.45	<0.02	0.02	0.02
Co	<0.10	<0.10	<0.05—0.6	<0.05	0.01	0.01
Cr	bdl—0.15	bdl	<0.05—2.4	<0.05	0.10	0.10
Cu	bdl—0.30	bdl	<0.05—0.7	<0.05	0.20	0.20
Fe	31—120	70—100	44—1,380	900—1,000	9.00	9.00
Mn	0.5—2.30	0.6—1.8	0.14—16	12	32.00	32.00
Pb	bdl	bdl	<0.5—3.3	<0.05	0.50	0.50
Ni	bdl—0.20	bdl	0.05—0.9	0.05—0.25	0.08	0.08
Zn	0.10—2.20	0.10—2.10	0.40—165	9—13	0.20	0.20

Note: Leachates I and II were generated in 4,000-ℓ tanks charged with typical municipal solid waste. Leachate III is an active Tucson city solid waste landfill.

^a nd, means not determined; bdl, means below detectable limits; bdl for the atomic absorption equipment used in mg/ℓ are Cd = 0.005, Cr = 0.05, Co = 0.05, Cu = 0.05, Pb = 0.5, Ni = 0.05, Mn = 0.05, Zn = 0.005, Al = 0.5, and Fe = 0.05.

From Fuller, W. H., Alesii, B. A., and Carter, G. E., *J. Environ. Sci. Health*, A14, 461, 1979. With permission.

undergoing biodegradation generally decrease in constituent concentration or solubility with time. Other factors related to environment conditions also alter the solubility of polluting constituents of the MSW landfill leachates and their consequent impact on soil liner integrity. For example, the effects of pH change and aqueous dilution on the solubility of chromium (CrVI + CrIII) of MSW leachate is illustrated in Figure 7.²⁵

During the first few years after the establishment of the landfill, leachate composition changes more rapidly than at any other stage in the biodegradation cycle.^{26,27} The occurrences and magnitude of these changes appear to be common to all biodegradations under anaerobic conditions similar to the sanitary landfill. During the first 3 years of biodegradation, changes were found by Fuller and Alesii to be approximately as follows:²⁵

- pH rises from 3.5 to 7.0
- Oxidation-reduction potential rises from a low of about 60 to 150 Eh
- Sulfide rises several fold

Table 9
SOME MUNICIPAL SOLID WASTE LANDFILL LEACHATE CONSTITUENTS
USED AS INDICATORS OF LEACHATE CONTAMINATION OF
UNDERGROUND WATER

Physical	Chemical:Organic	Chemical:Inorganic	Biological
Appearance	Phenols	Total biocarbonate	Biochemical oxygen
pH	Chemical oxygen demand (COD)	Solids (TSS, TDS)	demand (BOD)
Oxidation-reduction potential	Total organic carbon (TOC) Volatile acids	Volatile Solids Chloride	Coliform bacteria (total, fecal; fecal streptococcus)
Conductivity	Tannins, lignins	Phosphate	Standard plate count
Color	Organic N	Alkalinity and acidity Nitrate-N	
Turbidity	Ether soluble (oil and grease)	Nitrate-N Ammonia-N	
Temperature	MBAS	Sodium	
Odor	Organic functional groups as required Chlorinated hydrocarbons	Potassium Calcium Magnesium Hardness Heavy metals (Pb, Cu, Ni, Cr, Zn, Cd, Fe, Mn, Hg, As, Se, Ba, Ag) Cyanide Fluoride	

From U.S. Environmental Protection Agency, Process Design Manual for Land Treatment of Municipal Wastewater, EPA-625/1-77-008, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977, 1.

- Rate of sludge formation and accumulation rises greatly with time
- Free volatile acids decrease from an original maximum, about 10-fold
- Soluble TOC decreases about 100-fold, BOD and COD roughly follow the trend of TOC
- Electrical conductivity (EC) and soluble inorganic salts decrease several fold
- Soluble heavy metal concentration decreases rapidly, sometimes completely disappearing from detection with time
- Soluble Fe decreases as much as 5-fold
- Soluble P decreases several fold, sometimes disappearing from ready detection
- Common soluble ions (Ca, Mg, Na, K, Cl, and SO₄, for example) decrease markedly with time but do not disappear. They are always present though sometimes at relatively low levels. They accumulate on the particle solid surfaces as precipitates and absorbates where they can still be active in penetrating the site-enveloping soils.

Should the intimate environment within the landfill proper be altered by drying, rewetting, or freezing and thawing, the solubility of the constituents in the leachate can alter drastically and in some instances irreversibly. Changing the leachate to distilled water in Anthony sandy loam, for example, showed that attenuated iron from MSW leachate effectively resisted desorption by water²⁵ (Figure 8). Similar results were obtained with MSW landfill leachate enriched with 10 metals, As, Cd, Cr, Cu, Hg, Ni, Pb, Se, V, and Zn and passed through eleven reference soils from seven most prominent orders. When breakthrough had occurred, each soil column was segmented and each segment extracted with water and with 0.1 N HCl. The results indicated:⁴

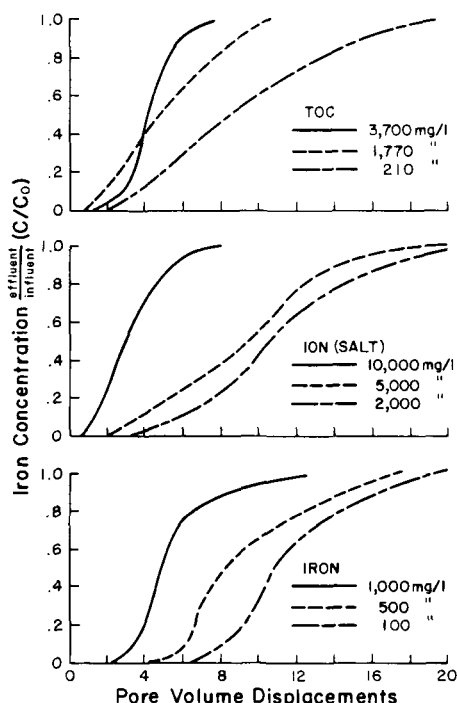


FIGURE 6. Influence of total organic carbon (TOC), salts (ION), and iron on the migration rate of Fe from MSW leachate through Kalkaska sand. (From Fuller, W. H., *Liners of Natural Porous Materials to Minimize Pollutant Migration*, EPA-600/S2-81/122, U.S. Environmental Protection Agency, MERL, Natl. Tech. Info. Serv., Springfield, Va., 1981, 73.)

- Metal ions sorbed initially were most tightly held against desorption
- Coarse-textured soils (sands) released sorbed metals most easily
- Extraction with water desorbed only minimal (trace) amounts of the retained metals
- Dilute (0.1N HCl) acid leachings, in contrast, dissolved significant quantities of retained metal ions

When a 3 year old leachate and dilutions with water of 75, 50, and 25% of the original concentration were passed through Ava silty clay loam, the retention of cadmium as exhibited by breakthrough curves (c/c_0) was further and further delayed at each leachate dilution. The delay occurred despite maintaining the same level of Cd (~ 200 mg/l) in the diluted influent. Cadmium in deionized water alone in another experiment did not appear in the soil-column effluent until after 10 pore volume displacements had occurred and (not shown) approached breakthrough (i.e., $c/c_0 = 1$) only after about 100 pvd.

Wetting and drying of 3 and 5 year old MSW leachates under vacuum (Table 10) resulted in a hysteretic effect where all of the soluble constituents of TOC, Cd, Ni, Zn, and Fe did not return into solution upon rewetting. The implication is that drying or cycling through dehydration/rehydration can be a means of lowering the solubility of certain contaminants in dilute aqueous solutions or leachates such as are generated in MSW landfills. Further research confirms dehydration does contain a valid and measurable hysteretic effect upon dehydration.²⁸ The practical significance of this has yet to be demonstrated under field conditions.

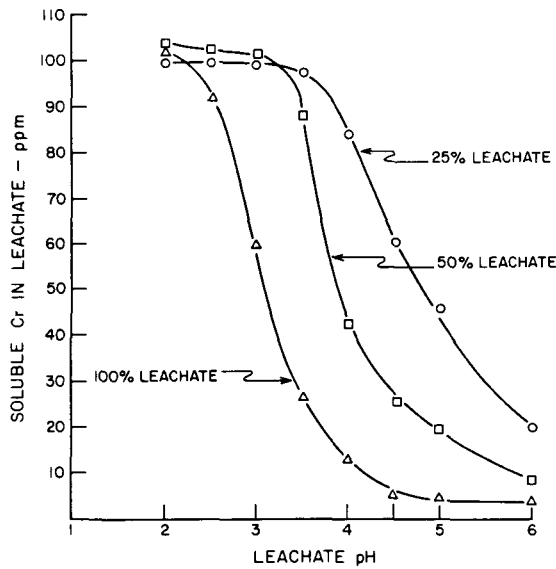


FIGURE 7. The influence of pH and aqueous dilution on the solubility of chromium in MSW landfill leachate. (From Fuller, W. H. and Alesii, B. A., *Environ. Sci. Health*, A14, 477, 1979. With permission.)

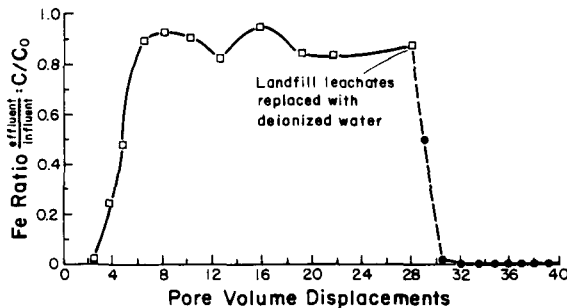


FIGURE 8. The attenuation of Fe of landfill leachate by Anthony sandy loam demonstrating the retention of Fe against leaching with water. (From Fuller, W. H., *Investigation of Landfill Leachate Pollutant Attenuation by Soil*, EPA-600/2-78-158, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1978, 186.)

Freezing results in a similar effect to dehydration, but certainly the physical mechanisms are not the same. Figure 9 compares the effect of five successive freezes on the solubility of Cd, Ni, Zn, and Fe and on total organic carbon (TOC) and salts as reflected by electrical conductivity (EC). Here the hysteresis effect appeared more pronounced than with dehydration. Moreover, successive freezes continued to take more and more constituents out of solution. Iron was most affected. Almost all of the soluble Fe resisted solubilizing upon thawing after about four freezes. The most pronounced effect was with the youngest leachate of 6 months' generation. The practical aspect is clouded by the associated damage to liners caused by freezing and thawing and the unlikelihood of MSW landfill or any other burial leachate freezing completely. Surface applied organics and wastes, however, may undergo freezing in cold climates. Again, these exploratory investigations only open avenues for rethinking modern waste disposal and unfortunately do not serve to solve practical problems

Table 10
INFLUENCE OF DRYING AND WETTING ON THE
SOLUBILITY OF THE TOTAL ORGANIC
CARBON CONSTITUENTS (TOC), Cd, Ni, Zn, AND
Fe OF MSW LANDFILL LEACHATES 3 AND 5
YEARS OLD

MSW leachate Identification No.	Batch	Percentage lost from solution after drying and wetting ^a				
		TOC	Fe	Cd	Ni	Zn
2—3 years old	1	36	88	0.44	2	0.5
	2	35	96	1.00	4	1.5
4—5 years old	1	21	98	17	16	23
	2	23	98	19	14	21

^a Figures represent an average of three replicates from each leachate batch.

From Fuller, W. H. and Alesii, A. B., *Environ. Sci. Health*, A14, 559, 1979. With permission.

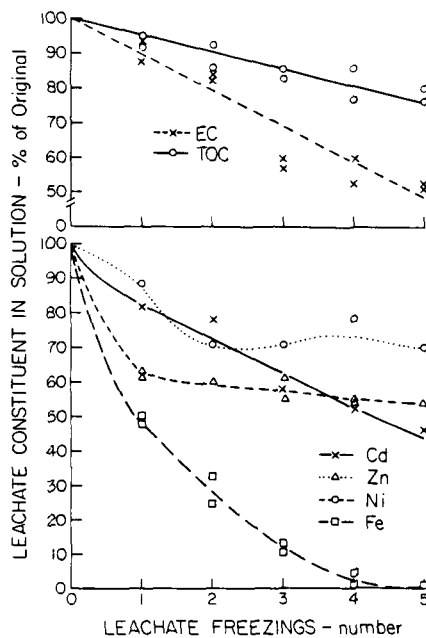


FIGURE 9. The effect of successive freezes and thaws on the solubility of Cd, Ni, Zn, and Fe and total organic carbon (TOC) and salt (EC) constituents in MSW landfill leachate 3 years old. (From Fuller, W. H. and Alesii, B. A., *Environ. Sci. Health*, A14, 1979, 482. With permission.)

for waste management. Drying also causes shrinking and cracking of liners and may be viewed in an unfavorable light since it could cause liner failure.

4. *Kinds of Soil Liners for Landfills*

Burial-type wastes, landfills in particular, need different kinds of liners for different functions. The general topic of lining of waste impoundments and disposal facilities with special emphasis on use of man-made materials is addressed by Haxo of Matrecon, Inc.² and personnel of Research Triangle Institute.²⁹ Our comments here relate to the uses of soil and soil material as liners and barriers where some leakage is permitted and even encouraged.

Soil liners for landfills may be roughly grouped into five categories:

1. *Compacted undisturbed soil* in place, usually natural soils which have permeabilities of 10^{-5} cm s⁻¹ to 10^{-7} cm s⁻¹ may need some mixing
2. *Highly compacted disturbed soil liner*, usually clays of 20 to 30% <2- μ m clay, to permeabilities no greater than 10^{-7} cm s⁻¹
3. *Coarse sand layers* for collecting gases and/or leachates collection and discharge
4. *Fine to medium grade gravels* for gas and/or leachate collection and channeling
5. *Soil layer liner* for cover vegetation growth, usually fertile loams

B. Trenches and Encapsulations

Trenches for sanitary landfills should involve compacted soil liners to insure reasonable confinement of leachate pollutants. The cover also will require attention, just as for the more conventional sanitary landfill. Typically, for the trench method of sanitary landfilling, the collection truck deposits waste into a trench where a bulldozer spreads and compacts it. The soil most recently excavated is used as daily cover.

Encapsulation implies that hazardous wastes are physically enclosed by an impervious encasement as described earlier. Encapsulation techniques have only recently emerged from the developmental and testing stages.³⁰ No large commercial scale encapsulation facilities have been designed and operated, although experimental scale units have been tried.

Containerized wastes, however, represent disposals that have been with us for some time. Where these wastes are of volumes smaller than the design capacity of the encapsulation unit, soil may be used to fill the voids between the container and encapsulated walls. On the other hand, where the containers are greater than the ordinary 0.2 m³ (54 gal), it is necessary to install compaction operations at the site.³¹

V. LINERS FOR SURFACE IMPOUNDMENTS

For this discussion, a surface impoundment is defined as a natural topographic depression, artificial excavation or like configuration, that is constructed on, below, or partly in the ground, is generally wider than it is deep, and is used for storage, treatment, or disposal of wastes in the form of liquids, semi-solids, or solids.³² Liners for fresh water impoundments, such as natural lakes, reservoirs, and farm ponds used for supply, collection of storm-water runoff, flood control, and irrigation will receive attention in the next section under "ponds". Surface impoundments require special soil manipulations because of the collection of water from rainfall, contaminated runoff, and aqueous effluents from industry containing a great variety and concentrations of potential organic pollutants, solvents, and hazardous wastes. Waste impoundments may be lined or unlined and range in area from a few tenths to over 100 ha. Most are shallow (0.5 to 1 m), but a few are excavated to as much as 10 m below the land surface, yet above the water table. Some depend on the construction of dikes or revetments. Often this kind of construction takes advantage of natural depressions or catchment landscapes. Also, surface waste impoundments may be single or multiple. The flow

of the latter may be in series of parallel arrangement as illustrated by the physical set-up for treatment of municipal sewage using aquaculture techniques.³³ Surface impoundments can be either discharging and nondischarging. The discharging impoundments lose liquids by evaporation and infiltration; nondischarging are designed for containment. Impoundments designed to lose liquids through seepage are referred to as percolation, infiltration, or seepage ponds or lagoons. These are constructed in permeable soils without lining because of the low risk of groundwater pollution from the disposal.

Seepage is undesirable for some impoundment disposals and, therefore, requires liner placement. Clay soils of low permeability (10^{-7} s^{-1}) are commonly used as preferred liners. Clay liners require compaction to 95% of maximum and chemical pretreatment such as salt-expanding modification explained earlier. Some impoundments are believed to be “self-sealing” as a result of fine particles, organic and inorganic colloids, algae, and atmospheric debris settling to the bottom and plugging or clogging the liner pores. Very few data appear in the literature regarding such a phenomenon, although the basis for “settling” impoundments involves some features of “self-sealing”. At present, this type of sealing is considered unreliable and should not be a critical part of the design. The purpose of “settling” impoundments is generally to separate the soluble from the insoluble constituents to permit some economic reuse of the clear liquid drained from the vicinity of the surface.

Biological treatment of wastewaters involves the use of oxidation ponds and aerated lagoons. Depths of these usually range from 1.0 to 2.5 m for the former and 3.5 to 5.0 m for the latter. Clay lining to achieve maximum compaction should be undertaken in all cases to prevent undesirable seepage to groundwater.

Pits are used most often to discharge special wastes. Abandoned aggregate (gravel and sand) pits are examples. Wastes introduced into such pits are often associated with disastrous effects on the quality of water tables and groundwaters. Usually, pits are not lined and are located in porous unconsolidated rock, stone, gravel, and sand that have little or no attributes for retention of polluting constituents. Such “pit and dumping” practices are not acceptable to modern society.

In summary, impoundment treatment may accomplish:

- Cooling of water
- pH adjustment
- Chemical coagulation
- Chemical precipitation
- Biological oxidation
- Settling of solids
- Water storage and reuse

Combinations of impermeable synthetic liners (e.g., plastic MN-21, 20 mil; EPDM-1/16 in.; CPE laminated 30 mil; PVC-10, 20 mil; Hypalon 10, 20, 30, 40 mil; neoprene, etc.) and natural clay soil on compacted clay bases are being used with increasing frequency in liner designs for impoundments. Again, it should be remembered that even the best liners will leak at some point in time. Therefore, the practices now being used may soon be only temporarily, in part at least, because of unsuspected failures both with natural soil and synthetic liners. Surface impoundments certainly should be highly restricted as to kind and concentration of toxic hazardous waste permitted disposal in this type of design. When properly constructed, surface impoundments are effective in waste disposal design, but greater attention in the future must center on containment, better lining design and practice, and more restrictions established for disposal of toxic and hazardous wastes and waste streams than have been permitted in the past.

VI. LINERS FOR FRESHWATER PONDS

A. Freshwater Ponds

Ponds are differentiated from surface impoundments, for this discussion, mainly on the basis of water quality. Ponds represent fresher water which can be utilized as a resource. In some cases, no treatment is necessary; in others, the pond itself is the center of a renovative process. Of the 2.2 million ponds built on private land up to 1970³³ many require some lining.

Physically, ponds have less surface area exposed per volume of water since, unlike surface impoundments, evaporation is not an objective nor particularly desirable. Ponds serve many purposes, such as:

- Flood and runoff control
- Reservoir and other storage
- Recreation
- Wildlife habitat and fishing
- Water supply for farm and home use
- Irrigation supply
- Stock ponds
- Fire protection
- Wastewater collection
- Oxidation ponds

B. Oxidative Ponds

Biological treatment offers rare opportunities for pollution control in ponds. They often are designed for wastewater treatment that eventually yields fresh water. In fact, the aeration or oxidation pond is the major detoxification method available for many organic compounds and masses of readily oxidizable wastewaters, such as those from the canning industry, prior to land treatment or utilization. The biological treatment pond requires that special attention be given to the soil to insure pollutant containment for treatment and environmental quality security. Most ponds should be constructed with highly impervious liners. Where clay liners are selected, they should be designed for the highest level of impermeability and maximum retention of water. The salt affected clay liners with compaction have proved to be effective in the arid Southwest where ponds have been established for a number of purposes including sewage water renovation. The Santee Recreation Project at Santee, Calif. is an example of sewage waste water renovation where a combination of filtrations through coarse material preceded pond purification and final collection in ponds for recreation use.³⁴ The Indian Bend Wash flood control project in Scottsdale, Ariz. was designed with a series of ponds for collection of runoff and flood waters for flood control, recreation, and irrigation of a golf course.³⁵ Soil liners for these ponds consisted of 60 cm of salt-expanded clay soil overlying a minimum of 2 m of compacted loam soil. Loss of water was due wholly to evaporation from the surface as verified by evaporative pans placed at the center of the lakes.³⁵

Oxidation ponds possess an advantage over stagnant systems for renovation of wastewaters abundantly supplied with biodegradable organics and certain chlorinated hydrocarbons having structures that are more susceptible to oxidative than reductive processes. Some chemical companies have used this method with success. Pond boundaries may or may not involve soil boundaries. Clay ($<2\ \mu\text{m}$) soils compacted to minimize water movement from seepage can be used, provided favorable depths of fine texture soil underlies the liner. Clay soil, containing at least 25 to 35% $<2\text{-}\mu\text{m}$ particles, should be imported to the area if sufficient supplies are not available near the pond site.

C. Sediment Collection Ponds

Often overlooked in waste disposal designs is runoff water from land treatment, landfill, or other disposal sites. Surface runoff, from precipitation events, usually carries fine sediments from exposed soil as a result of activity that surrounds the disposal operations. Ponds may effectively be used to collect the surface runoff, separate the sediments, and discharge quality water. The pond should be constructed large enough to allow sufficient sediment collection to minimize siltation of downstream surface water systems. Other soil modifications need to be undertaken in conjunction with the pond construction, such as diversion ditches to (1) channel waters into the pond and (2) divert the water out of the pond basin into an adequate receiving area or body of water for reuse. Leaching waters having had contact with the waste should not be included in the runoff water to be ponded.

The size and design of the pond will vary considerably with the intended function and with the:

- Intensity and seasonal amounts of precipitation
- Area climate and water balance of site
- Total drainage area of the site
- Site topography and slope characteristics
- Vegetation kind and density
- Retention time necessary for pollutant control

D. Embankment Ponds

Two major kinds of ponds, embankment and excavated ponds, predominate. The embankment ponds utilize natural stream beds or watercourses with construction of an embankment or dam across the depressions. The stream beds most often selected permit storing of 2 m (6 ft) or more of water. The land slopes may range from gentle to steep. The most favorable sites are those that require the least amount of earthfill, the side slopes are steep, and the slope to the valley floor permits a large area to be flooded. The purpose is assumed to be to

1. Minimize the area of shallow water
2. Avoid excessive evaporation
3. Minimize the growth of noxious aquatic plants

Site location, again, depends on intended use.

The nature of the soil at the embankment site determines the capacity of the pond to hold water. The soil layer and liner, whether natural and manipulated, must contain a high proportion of fine-graded particles and be thick enough to minimize water seeping out of the pond. Clay and silty clays make the most secure liners when kept continuously wet. Limestone areas must be avoided because of the characteristic presence of cracks, channels, and sinks. It is obvious that the site selection requires considerable study, soil borings, sampling, and laboratory testing of materials.

The base of the dam must be located on stable structures that provide complete resistance to the seepage of water. Coarse-textured soils such as gravel and sands make fairly solid foundations, but they leak. Fine-textured soils have low permeability, but also have low stability. Organic soils are unsatisfactory. Peats and mucks must be removed down to mineral soil or bedrock. Satisfactory foundation material is represented by a combination of coarse and fine material, such as gravel-sand-clay, gravelly clays, and clay-sand mixtures. Soils predominantly classed as gravels, sands, and silts provide the least satisfactory material because of unstable characteristics, leakage, and lack of cohesion.

Fill material must have enough strength to hold the dam. The determining factor in selecting

a site is the quality of the soil for building the dam. The soil must be either homogeneous originally or capable of being made homogeneous. Heterogeneous soils in a dam structure lead to piping, leaking, seepage, and finally loss of the structure. Lack of homogeneity is the one single factor, more important than any other, that has been responsible for dam failure. Generally, contractors demand at least 20% clay, but no more than 30% since clay shrinks and swells more than other particle sizes. Gravels and coarse sands should be avoided because they have a tendency to segregate causing piping, seepage, and leaks.

Spillway soils should not be constructed in loose sand. Their main requirement is to support vegetation sufficiently to prevent erosion. A good rule to follow is to keep the expected flow rate less than 8.5 m³/sec (300 cfs). Should there be need to exceed this rate, additional spillways should be constructed.

Finally, protection against soil erosion and excessive runoff concentration must be provided. The wise use of dense vegetation, for example, grassed waterways with good, permanent stands are most effective.

Engineering design and instructions for dam establishment are exacting. Many books and pamphlets are available in sufficient detail to preclude repetition here. Good instruction may be found in USDA Agricultural Handbook No. 387,³³ Schwab et al.,³⁶ and Blasley.³⁷

E. Excavated Ponds

The excavated pond is formed on relatively level land. The cost of excavation limits their size as compared with embankment ponds. Some are established on gently sloping land where a pit in conjunction with a dam can take advantage of both elevation change and excavation.³³ They are most popular on flat lands and where the demand of fresh water is small. They feature ease of maintenance, small requirements for erosion control, and freedom from flood damage. Three sources of water charge the excavated pond: surface runoff, shallow groundwater aquifer-water tables, and deep pumping.

Seepage loss must be kept to a minimum (assuming impoundment is the objective). The selection of the site for excavation requires foremost attention be given to the kind of soil available and the depth. The most desirable areas are located in fine-textured soils, clays, clay loams, loams, and where the soil depth extends well below the base of the excavation. Homogeneity of texture, freedom from excessive stratification, indurated layers, stones, boulders, and gravels, and distance from aquifers are necessary requirements. In fact, most of the requirements for both types of ponds, excavation and embankment, are similar. The size and relative dimensions vary with the intended use. The side slopes must relate to the nature of the material removed and be no steeper than the natural angle of stability imposed by the new environment and capacity to prevent sloughing. Vegetative cover along exposed sides, drainageways, and spillways should be established as soon as practical.

Sealing the pond floor after compacting is almost always required. Clay liners make the best material. At sites where the pond is likely to leak, new sealing quality soil should be imported. No less than 60 cm (12 in.) of compacted clay loam should be used as a liner. Some contractors recommend 120 cm (2 ft) of well compacted clay loams to prevent seepage losses.

F. Aquaculture Ponds

In areas where water supplies are short, as in arid and semiarid climates, aquaculture provides an attractive means of recovery and reuse of waste waters. The city of San Diego, for example, recovers potable water from municipal sewage by an aquaculture pretreatment process using water hyacinths (*Eichhornia crassipes*) followed by a 378 m³/d (100,000 gpd) spiral wound reverse osmosis unit. The hyacinths grow in ponds that process screened raw sewage (113.6 m³/d). The total procedure is as follows: screened raw sewage → ponds of water hyacinths → ultrafilter → (or rapid sand filter-mixed media) → spiral wound reverse

osmosis → activated carbon → disinfection → storage → used for sod field and/or discharge back to the waste program and/or to river recharge.³⁸

The surface of the ponds support duck weed (*Lemna minor*) and some lesser fairy moss (*Azolla caroliniana*) to keep algae growth under control, in addition to the production of water hyacinths. The hyacinths absorb the plant nutrients (N-P-K-trace elements), some heavy metals, and some toxicants. The harvested plant material may be anaerobically biodegraded to methane. Sedimentation of detrital material becomes a buffer part of the ecosystem. The bottom of the pool is anaerobic (30 cm), but the upper 60 cm is aerobic, with the middle area a metabolic equilibrium buffer. The aquaculture ponds are arranged in series such that the first pools yield plant material higher in absorbed constituents (e.g., heavy metals) than the latter pools. The cleaner and hazardous-free water of the latter pools yields plant material suitable for supplemental animal feed (horses, goats, rabbits, ducks, and chickens) and some plants are harvested and composted for garden use. The sludge from the methane production may be applied to the land as a soil conditioner.

Another example of pond usage for waste control was discussed in Vol. 1, Chapter 3 and referred to as “the cypress dome process”, a natural tertiary treatment filter.³⁹ Duck weed (*Lemna purpusilla*) and *Spirodela oligarhiza* are the principal plants grown in the cypress dome ponds. The plants act as a blotter, absorbing and concentrating the undesirable effluent constituents. Decomposition of the plant material again releases the nutrients for absorption by the cypress trees and enhancing the growth rate. The effluent can be shifted from one pond to another. The final disposition of the “treated” effluent is recharge to the underground water, relatively free of nutrients and effluent microorganisms not indigenous to the cypress ponds. The treated water that filters into the groundwater is claimed to be equivalent to that from a conventional tertiary treatment. The surface water of the domes is continuous with the surrounding water table in the pine woods which fluctuates appreciably with the change in season. The cypress domes have a natural blue-clay soil lining that appears to be well suited for retention of pollutant constituents in the sewage effluent, despite the combination of sandy soil and shallow groundwater aquifers.

The generalized cross section through most marshlands indicates a variability in soils of fine textures.⁴⁰ The predominant natural liner texture of many marshlands is sandy clays and clayey sands, which are favorable liner material for pollutant retention.⁴⁰ Quartz sand below an organic layer often characterizes the lip of the marshlands. When the marsh ponds are full, lateral movement may be expected to take place providing the adjacent areas with reasonably high-quality renovated water for irrigation purposes.

REFERENCES

1. **Fuller, W. H.**, Liners of Natural Porous Materials to Minimize Pollutant Migration, Rep. U.S. EPA-600/S2-81-122, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1981, 73.
2. **Matrecon, Inc.**, Lining of Waste Impoundments and Disposal Facilities, EPA SW-870, U.S. Environmental Protection Agency, OWWM, Cincinnati, Ohio, 1980, 385.
3. **Artiola, J. and Fuller, W. H.**, Limestone liners for landfill leachates containing beryllium, cadmium, iron, nickel, and zinc, *Soil Sci.*, 129, 167, 1980.
4. **Korte, N. E., Skopp, J., Fuller, W. H., Niebla, E. E., and Alesii, B. A.**, Trace element movement in soils: influence of soil physical and chemical properties, *Soil Sci.*, 122, 350, 1976.
5. **Fuller, W. H.**, Investigation of Landfill Leachate Pollutant Attenuation by Soils, U.S. EPA-600/2-78-158, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1978, 219.
6. **Fuller, W. H.**, Movement of Selected Metals, Asbestos, and Cyanide in Soil: Application to Waste Disposal, U.S. EPA-600/277-020, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1977, 243.
7. **Fuller, W. H.**, Soil-waste interactions, in *Disposal of Industrial and Oily Sludges by Land Cultivation*, SCS, Engineers Symp. Houston, Resour. Supt. and Mngt. Assoc., Harthfield, N.J., 79, 1980.

8. **Fuller, W. H.**, Soil modification to minimize movement of pollutants from solid waste operations, *Crit. Rev. Environ. Control*, 9, 213, 1980.
9. **Korte, N. E., Skopp, J. M., Niebla, E. E., and Fuller, W. H.**, A baseline study of trace metal elution from diverse soil types, *Water Air Soil Pollut.*, 5, 149, 1975.
10. **Brown, K. and Associates, Inc.**, Hazardous Waste Landfill Treatment, SW-874, SHWRD, MERC, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1983, 974.
11. **McDowell, C.**, Progress report on development and use of strength tests for subgrade soils and flexible base materials, *Proc. Highw. Res. Board*, 26, 484, 1946.
12. **Burmister, D. M.**, Environmental factors in soil compaction, *Am. Stds. Test. Methods*, STP, 377, 47, 1964.
13. **Coates, D. F. and Yu, Y. S., Eds.**, Pit Slope Manual, Waste Embankments, CANMET Rep. T I-1, Canada Center of Mineral and Energy Technology, Ottawa, Canada, 1978, 187.
14. **Stewart, W. S.**, State-of-the-Art Study of Land Impoundment Techniques, EPA-600/2-78-196, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1978, 67.
15. Bureau of Reclamation, Lining for Irrigation Canals, Including a Progress Report on the Lower Coastal Canal Lining Program, U.S. Department of Interior, Washington, D.C., 149, 1963.
16. Bureau of Reclamation, Design of Small Dams, 2nd ed., U.S. Department of Interior, U.S. Government Printing Office, Washington, D.C., 186, 1973.
17. **Parks, C. F. and Rosene, R. B.**, Preventing Losses of Industrial and Fresh-Water from Pits, Ponds, Lakes, and Canals, Preprint No. EQC-64, American Institute of Mechanical Engin., Environmental Quality Conf., 1971, 351.
18. **Artiola, J. and Fuller, W. H.**, Effects of crushed limestone barriers on chromium attenuation in soils, *J. Environ. Qual.*, 8, 503, 1979.
19. **Fuller, W. H. and Artiola, J.**, Use of limestone to limit contaminant movement from landfills, in Land Disposal of Hazardous Wastes, Shultz, D. W., Ed., Proc. 4th Annu. Res. Symp., San Antonio, EPA-600/9-78-061, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1978, 282.
20. **Artiola-Fortuny, J. and Fuller, W. H.**, Absorption of some monohydroxy-benzene derivatives by soil, *Soil Sci.*, 133, 18, 1982.
21. **Griffin, R. A. and Shimp, N. F.**, Attenuation of Pollutants in Municipal Landfill Leachate by Clay Liners, EPA-600/2-78-157, U.S. Environmental Protection Service, Cincinnati, Ohio, 1978, 147.
22. **Alesii, B. A., Fuller, W. H., and Boyle, M.**, Effect of leachate flow rate on metal migration through soil, *J. Environ. Qual.*, 9, 119, 1980.
23. **Fuller, W. H., Alesii, B. A., and Carter, G. E.**, Behavior of municipal solid waste leachate. I. Composition variations, *J. Environ. Sci. Health*, A14, 461, 1979.
24. U.S. Environmental Protection Agency, Process Design Manual for Land Treatment of Municipal Wastewater, EPA-625/1-77-008, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977, 1.
25. **Fuller, W. H. and Alesii, B. A.**, Behavior of municipal solid waste leachate: in soil, *Environ. Sci. Health*, A14, 559, 1979.
26. **Chian, E. S. and DeWalle, F. B.**, Evolution of Leachate Treatment, Vol. 1, Characterization of Leachate, EPA-600/2-77-186a, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977a, 210.
27. **Chian, E. S. and DeWalle, F. B.**, Evolution of Leachate Treatment, Vol. 2, Biological and Physical-Chemical Process, EPA-600/2-77-186b, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977b, 245.
28. **Bitterli, R.**, Freezing and Drying: Effects on the Solubility of Municipal Solid Waste Leachate Constituents, M.S. thesis, The University of Arizona, Tucson, 1981, 37.
29. Research Triangle Institute, Performance of Clay Caps and Liners for Disposal Facilities, Final Rep., EPA Contr. No. 68-03-3149, Research Triangle Institute, Research Triangle Park, N.C., 1983, chap. 8.
30. U.S. Environmental Protection Agency, Handbook for Remedial Action at Waste Disposal Sites, EPA-625/6-82-006, U.S. Environmental Protection Agency, MERL, ORD, Cincinnati, Ohio, 1982, 497.
31. **Lubowitz, H. and Wiles, C.**, Encapsulation technique for control of hazardous wastes, in Land Disposal of Hazardous Wastes, Shultz, D., Ed., Proc. 4th Annu. Res. Symp., EPA-600/9-78-016, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977, 342.
32. Geraghty and Miller, Inc., Surface Impoundments and Their Effects on Groundwater Quality in the United States — A Preliminary Survey, EPA-590/9-78-004, U.S. Environmental Protection Agency, ODW, Washington, D.C., 1978, 275.
33. U.S. Department of Agriculture, Soil Conservation Service, Ponds for Water Supply and Recreation, Agric. Handbo. No. 387, Washington, D.C., 1971, 55.
34. **Merrell, J. C., Jr., Kalko, A., and Pantler, H. E.**, The Santee Recreation Project, Santee, Calif. Summary Rep. 1962—64, Publ. No. 999-WP-27, Public Health Service, Washington, D.C., 1965, 25.
35. **Fuller, W. H.**, *Management of Soils of the Southwest Desert*, The University of Arizona Press, Tucson, 1975, 102.

36. **Schwab, G. O., Frevert, R. K., Edminister, T. W., and Barnes, K. K.,** *Soil and Water Conservation Engineering*, 3rd ed., John Wiley & Sons, 1981, chaps. 5 and 6.
37. **Beasley, R. P.,** *Erosion and Sediment Pollution Control*, The Iowa State University Press, Ames, 1972, chap. 10.
38. **Conn, W. M.,** Municipal Sewage Treated to Potability Using Aquaculture Through Membranes, City of San Diego, Water Utilities Department, Metropolitan Wastewater Division, San Diego, Calif. 1983, 15.
39. **Ewel, K. C. and Odum, H. T.,** Cyprus domes: nature's tertiary treatment filter, in *Utilization of Municipal Sewage Effluent and Sludge on Forest and Disturbed Land*, Sopper, W. E. and Kerr, S. N., The Pennsylvania State University Press, University Park, 1979, 103.
40. **Spangler, F. L., Sloey, W. E., and Fetter, C. W., Jr.,** Wastewater Treatment by Natural and Artificial Marshes, EPA-600/2-76-207, U.S. Environmental Protection Agency, RSKERL, Ada, Okla., 1976, 171.



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

Chapter 3

GASES, ODORS, AND AEROSOLS

I. SCOPE

Gas, odor, and aerosol emission all share the atmosphere (air) as a common transport system. Also, all three emissions become most concentrated and obnoxious under conditions of limited oxygen (i.e., aeration) designated as anaerobic and/or anoxic. These emissions originate from a great number and variety of organic wastes. More often than not, all three occur together, evolving from a single or multiple source and varying as a serious nuisance depending on the nature of the specific environment during biodegradation. In the presence of an abundance of oxygen, the end product gases are primarily carbon dioxide (CO_2) and nitrogen (N_2), with water (H_2O) present in both gaseous and liquid forms. In the absence of atmospheric oxygen (O_2), intermediate breakdown products of organic matter and synthesized intermediate compounds accumulate, in addition, notably methane (CH_4), carbon monoxide (CO), hydrogen (H), hydrogen sulfide (H_2S), and numerous volatile odorous organics as identified in Table 1.¹

The seriousness of waste gas, odor, and aerosol generation receives little attention in contrast to waste leachates. Yet, documentary evidence of damage or injury resulting from landfill leachates is lacking, whereas extensive damage to property and serious injuries, some of which have resulted in death, have been attributed to concentrations of landfill gases. Malodors from organic wastes can affect the aesthetic, economic, mental, and physical health of a community. One of the greatest concerns of a community over waste disposal, both social and political, relates to malodors. Although there is no relationship with specific organic diseases or toxicities of a gas, odors incite responses such as mental stress, allergy, loss of appetite, respiration stress, nausea, vomiting, and insomnia. Unfortunately, many odorous compounds can be detected by the senses at extremely low concentrations. The seriousness of gases, odors, and aerosols generated from wastes has sent scientists in search of control measures and remedial waste management practices. Air cleaning techniques for removal of air pollutants include water scrubbing, burning, and sorption with lime, resins, and charcoal, to name a few. The cost for this is high. Bohn suggests the use of soil filters, partly because soil is comparatively less expensive than other materials and partly because soil is an effective absorber of malodorous gases and other waste site emissions.² He further points out that the use of soil filters in western Europe is much more advanced than in the U.S.³ The practicality of soil for eliminating or reducing odor was well known long before air pollution was recognized to have such a hazardous influence on the general health of society.

II. GAS CONTROL

A. Origin and Nature of Waste Gases

Waste gases originate primarily from anaerobic biodegradation of organic materials. Microbial activity is almost always responsible for mineralization or biodegradation of organic molecules in soils and waters. Large quantities of gas accumulate from biodegradation of municipal solid waste (MSW) disposals. Readily decomposable organic materials from cannery, paper and pulp, leather, textile, oil, and agriculture industries, for example, also contribute wastes that yield gases when biodegradation occurs under anaerobic (and sometimes fluctuating anaerobic-aerobic) conditions. The MSW landfill will be used as an example. The route of biodegradation of organic materials of different sources and composition does not differ appreciably, only the rate differs significantly.

Table 1
SELECTED VOLATILE ODOROUS ORGANIC COMPOUNDS¹

Alcohols	<i>n</i> -Decaldehyde	Diisopropylamine
Methanol	Ethylformate	Dibutylamine
Ethanol	Methylacetate	Diisobutylamine
<i>n</i> -Propanol	Isopropylacetate	Ammonia
Isopropanol	Isopropylpropionate	Indole
<i>n</i> -Butanol	Isobutylacetate	Skatole
Isopentanol	Acetone	
	2-Butanone	Sulfur-containing
Carbonyl-containing	3-Pentanone	Hydrogen sulfide
Acetic acid	2,3-Butanedione	Carbonyl sulfide
Propionic acid	3-Hydroxy-2-Butanone	Dimethyl sulfide
<i>n</i> -Butyric acid		Diallyl sulfide
Isobutyric acid	Nitrogen-containing	Carbon disulfide
<i>n</i> -Valeric acid	Methylamine	Dimethyl disulfide
Isovaleric acid	Dimethylamine	Methanethiol
Formaldehyde	Trimethylamine	Ethanethiol
Acetaldehyde	Ethylamine	Propanethiol
Propionaldehyde	Triethylamine	<i>t</i> -Butylthiol
<i>n</i> -Butyraldehyde	<i>n</i> -Propylamine	<i>t</i> -Amythiol
Isobutyraldehyde	Isopropylamine	
<i>n</i> -Valeraldehyde	<i>n</i> -Butylamine	Simple organics
<i>n</i> -Hexaldehyde	<i>n</i> -Amylamine	CO ₂
<i>n</i> -Octaldehyde	<i>n</i> -Hexylamine	Methane

Whereas the composition of the gases varies somewhat with different environmental conditions, the quantity varies considerably with the age of the landfill and availability of the waste residues to microbial utilization. See the biological section of Volume 1, Chapter 1 of this book. Measured landfill gas composition reported at the Mountain View landfill in California appears to be representative of low levels of MSW landfill emissions.⁴ Methane (CH₄) and carbon dioxide (CO₂) accounted for about 78% of the total. This value is slightly lower than that from test results at Palo Verdes and Sheldon-Arlela, Calif., where the composition ranged from 50 to 56% CH₄, 40 to 45% CO₂, 1% N₂, and 0.1% O₂, with some heavy hydrocarbons and hydrogen sulfide.⁴ Compositions, of course, vary with the size and depth of the landfill and rate of withdrawal as reflected by leakage of air into the waste matrix.

An empirical equation developed to approximate general gas production follows:⁴

$$\text{SCFD} = (18.77)(10^6)(Ah/R^2) \quad (1)$$

where

$$\begin{aligned} \text{SCFD} &= \text{production rate (standard-cc/d)} \\ A &= \text{area of landfill in acres} \\ h &= \text{depth in feet} \\ R &= \text{radius of influence of wells in feet} \end{aligned}$$

The life of a production well in a landfill is not forever. The estimated life is given by the equation:

$$t = (2.49)(10)^{-3} CR^2 \quad (2)$$

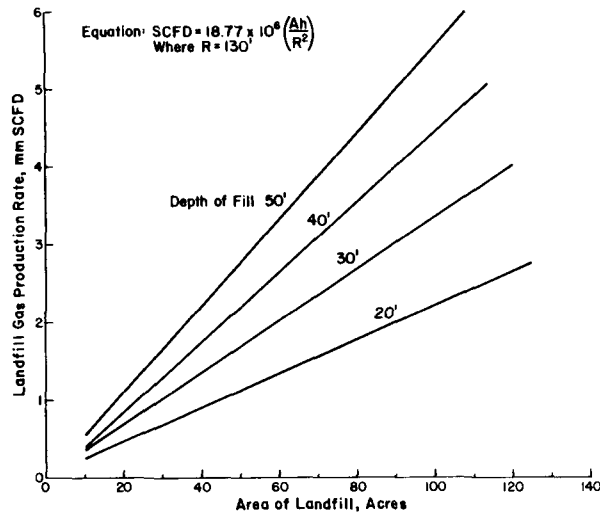


FIGURE 1. Illustration of the production of landfill gas vs. landfill area and depth. (From Blanchet, M. J. and Staff, Treatment and Utilization of Landfill Gas: Mountain View Project Feasibility Study, EPA SW-583, U.S. Environmental Protection Agency, OSW, and Pacific Gas and Electric Co., San Francisco, MERL, Cincinnati, Ohio, 1977, 51.)

where

- t = life in years
- R = radius given above
- C = the fraction of carbon in the MSW converted to CH_4 and CO_2

The production rate as related to landfill area and depth is illustrated graphically in Figure 1. The CO_2 concentrations in the gas mixtures is the highest just after waste placement and cover. The CH_4 production is lowest at this time, but increases sharply to a maximum that plateaus to a practical level (Table 2) according to Merz and Stone.⁵ Accumulations of water in the landfill due to rainfall and/or subsurface rise in water tables causes an increase in rates of CH_4 production. Alone, CH_4 is not explosive, but it is highly explosive when associated at concentrations of 5 to 15% with air.

B. Gas Movement Through Soil

Gas movement occurs principally by two mechanisms: diffusion and mass (convective) transfer. Diffusion occurs according to concentration gradients and is governed by molecular motion. Examples are exchanges of oxygen and carbon dioxide during respiration by plant roots or microbes. Mass transfer by convection occurs along lines of overall pressure gradients and displacement of all gaseous components occurs together in the same directions. An example of mass transfer is displacement of gases in the top of the soil profile during a change in barometric pressures or release of gases from an underground filtration system.

Diffusive transfer follows Fick's law of diffusion:

where

$$q_m = \text{mass discharge flux density (units } ML^{-2}T^{-1}) \quad (3)$$

Table 2
**CHANGE IN PRODUCTION OF N₂,
 CO₂, AND CH₄ AS INFLUENCED BY
 AGE OF MSW LANDFILL DEPOSIT**

Time interval since start of cell completion (months)	Average percent by volume		
	N ₂	CO ₂	CH ₄
0—3	5.2	88	5
3—6	3.8	76	21
6—12	0.4	65	29
12—18	1.1	52	40
18—24	0.4	53	47
24—30	0.2	52	48
30—36	1.3	46	51
36—42	0.9	50	47
42—48	0.4	51	48

From Merz, R. C. and Stone, R., Special Studies of a Sanitary Landfill, U.S. Department of Health, Education and Welfare, Washington, D.C., 1970.

Δc = concentration drop over L
 L = effective path length
 D = diffusion coefficient ($L^{-2}T^{-1}$)

The coefficient D may be approximated by

$$D = (0.66)\theta_a D_o$$

where 0.66 is a dimensionless, empirical factor and Θ_a is the air-filled porosity.⁶ The units of q_m and c are interrelated; if c is $kg\ m^{-3}$ then q_m will be $kg\ m^{-2}\ s^{-1}$.

Using the Mountain View landfill,⁷ a mass diffusion rate of CO₂ can be calculated. Given are

$$D_o = 1.4\ m^2d^{-1}\ (20^\circ C)$$

$$\theta_a = 0.22$$

$$L = 1\ m$$

$$C_o^* = 30\% \text{ (by volume)}$$

The concentration on a mass basis may be calculated assuming an ideal gas:

$$\begin{aligned}
 C_o &\approx \left(\frac{30}{100}\right) (0.044\ kg\ mol^{-1})(44.6\ mol\ m^{-3}) \\
 &= 0.59\ kg\ m^{-3}
 \end{aligned}$$

The effective diffusion coefficient D is

$$D = (0.66)(0.22)(1.4) = 0.20 \text{ m}^2\text{d}^{-1}$$

Therefore, the mass flux density is

$$q_m = (0.20)(0.59)/1 \approx 0.12 \text{ kg m}^{-2}\text{d}^{-1}$$

(equivalent to over 1000 lb/a/d). Generally, mass units are preferable, but the flux density could be calculated on the basis of a volume of CO_2 at atmospheric pressure giving a value of about 0.061 md^{-1} (equivalent to about $100 \text{ m}^3/\text{ha/d}$ ($8700 \text{ ft}^3/\text{a/d}$)).

Gas diffusion through soil occurs in accordance with differences in partial pressure or concentration of the various gases. The availability of pore spaces for gases is lessened by (1) extent of compaction and (2) soil water. Interchange of gases or aeration is very slow in water logged soils as the aeration porosity is nearly eliminated. A low aeration porosity leads to oxygen deficiencies, both in the soil and the buried solid waste material. Anaerobiosis, as free oxygen supplies diminish, is accompanied by an increase of incompletely oxidized organic gases.

The other major mechanism for gaseous transfer is by convection. The process is fully equivalent to Darcian flow for liquids, in fact, the air permeability for a dry soil is exactly the intrinsic permeability. Thus, the volume flow per unit area is q_D given by

$$q_D = (k/\rho)(\Delta p/L) \quad (4)$$

with $\Delta p/L$ the pressure gradient, i.e., pressure drop divided by the length of flow. The mass density ρ is for whatever gas is considered and k is the air permeability. Gas permeability is highly dependent on water content. Flow takes place through the air filled pores, so the effective rate of mass transfer decreases rapidly with increasing water content.

C. Gas Control

Attempts to control waste gases in burials have followed four major avenues of action:

1. Reduce gas production to safer handling levels
2. Channel gas movement to safe venting or dissipation in the atmosphere using gas barriers, trenches, channels, piping, and vents
3. Collection and absorption of gases by liquids and solids
4. Chemical combination

1. Reduction in Production

The most direct and effective way to reduce gas methane production in MSW landfills is to (1) decrease the activity of the microorganisms or (2) change the composition of the microflora. There are two main ways of accomplishing these objectives:

1. Prevent excessive water from infiltrating the landfill as much as possible via sealing
2. Provide some means of aeration to keep the biodegradation aerobic in order to accelerate oxidation of carbon compounds to CO_2 and H_2O

Gas concentrations, reaching explosive proportions, can develop in all landfills and accumulations of readily biodegradable organic wastes. The main objective in designs for organic waste burials must include methods for controlling methane gas from building into concentrations. Cautious planning, also, should extend to land use decisions after closures

of burials. For example, sealing the cover with asphalt for a parking lot without first allowing for free and safe exit of gases could lead to property damage and human injury.

2. Channels, Vents, Piping, Cover Control, and Barriers

Mechanical or physical designs for favorable manipulation of gases are varied and numerous. The cover design, layering, lining, and trenching have been fully discussed in Volume II, Chapter 6. Liner control, therefore, will not be repeated unnecessarily in this chapter. Physical methods of collection and dispersion represent the most practical means of controlling the gas concentration hazard in burials.

Properly designed covers help control landfill and other organic waste burials by reducing gas generation, accumulation, and migration from the site. Yet, the most cautious design may fail without the utmost attention to eliminate areas with aquifer structures passing underneath, through, or near the disposal facility. The greater the distance from such structures the safer the control. Aquifers near land surfaces may carry water only intermittently. A dry or partly dry aquifer provides a dangerous channel for carrying gases great distances from the waste site.

Most landfills require some form of physical channeling, collection, and venting of the gases generated from solid wastes. Physical systems involving permeable barriers, permeable trenches and channels, gas collection systems, vents, and a combination of these must be provided as part of the design. Designs for control of gas flow also include soil manipulations, such as:

1. Segregation by textures — fine-grained clay loams for cover and vertical barriers
2. Formation of special soil barriers — such as compacted fine-textured clay to direct gas flow or diffusion
3. Increased soil cover thickness
4. Layered cover and base support to permit vegetative growth and also prevent water infiltration and with resulting gas damage
5. Special soil textures for trenches, channels, and vents of porous soil materials like gravels and sands, often called gas flow barriers or vents

Design structures that relate to these soil modifications are reviewed in Chapter 2.

3. Collection and Absorption of Gases

Earth materials (soil, compost, and limestone) have a substantial capacity to control the nuisance and hazardous effects of waste gases. The subject of soil and compost filters to remove low concentrations of pollutant gases from air streams will be reviewed at the end of this chapter. Removal techniques also include water scrubbing (with and without added chemicals), burning, and sorption by activated charcoal. Flue gas cleaning is accommodated by collecting the obnoxious gases in slurries of CaCO_3 , $\text{Ca}(\text{OH})_2$, and Na_2SO_3 solution. The cost of these treatments is high, often prohibitive.³ Just like odor control, however, one of the most effective methods of gas elimination is good housekeeping, particularly where animal feeding and production is involved.

Collection of gases is also expensive. Single fan/vent collection systems are the least expensive, fairly easy to keep up, but are limited to relatively small sites (2.5 to 3.0 ha).⁸ The manifold collection system is more costly, more complicated, and requires considerable upkeep. Various designs for collection and venting gases are used in a great number of old landfills as part of remedial techniques as well as newly designed burials. Some of these are illustrated in Figures 2 and 3.

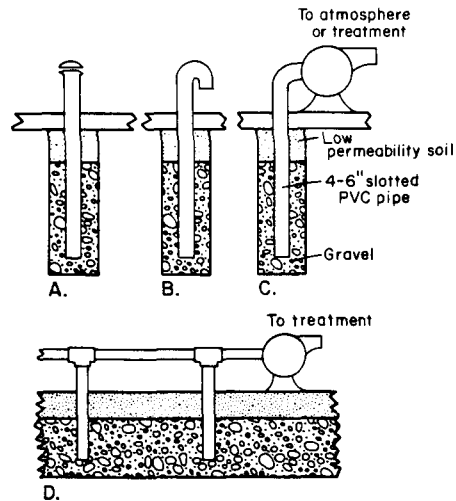


FIGURE 2. Various designs for collection and venting gases. (A) Atmospheric vent, mushroom top; (B) atmosphere vent, "U" top; (C) forced ventilation; and (D) vertical pipe vent connected to forced ventilation manifold system. (From U.S. Environmental Protection Agency, Handbook for Remedial Action of Waste Disposal Sites, EPA-625/6-82-006, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1981, 237.)

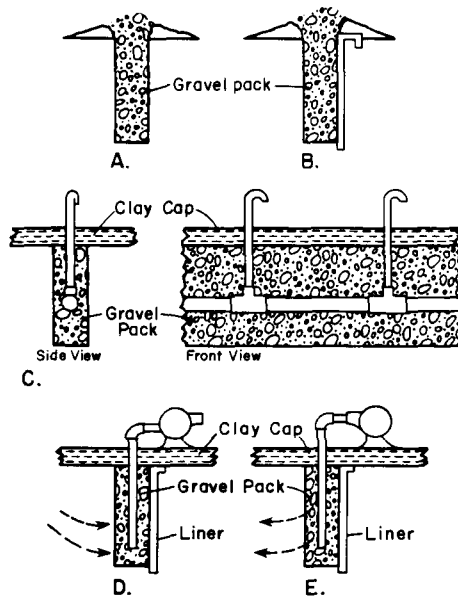


FIGURE 3. Illustration of trench liners. (A) Open trench; (B) open trench with liners; (C) closed trench liner with laterals and risers; (D) induced draft; and (E) air injection. (From U.S. Environmental Protection Agency, Handbook for Remedial Action of Waste Disposal Sites, EPA-625/6-82-006, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1982, 237.)

4. Chemical Combination

Chemical treatment of hazardous waste is not included as part of a soil treatment system except as chemical treatment relates to final disposal in soil. Physically, about 90% of hazardous waste by weight occurs in the liquid waste stream.⁹ Approximately 40% of this is inorganic, representing mixtures of acids, bases, heavy metals, and pesticide waste. A report by Landreth and Rogers⁹ contains a list of chemical methods, some of which relate to chemical combination and some to gas control:

- Chlorination
- Wet-air oxidation
- Decomposition by acids and bases
- Chemical oxidation
- Biological degradation
- Catalysis
- Photochemical processes
- Low-temperature microwave discharge
- Activated carbon adsorption

D. Gas Monitoring

Gas generation from burials of significant amounts of organic materials, whether landfills, trenches, encapsulations, impoundments, lagoons, or ponds, continues for many years after site closure depending on a number of circumstances, but primarily on the kind of waste and quantity. MSW landfills, for example, evolve gas for 20 years or more after closure.¹⁰ Impoundments also continue gas production after closure. In some instances gas production increases due to less aeration and the establishment of fully anaerobic conditions.¹⁰ Monitoring, consequently, becomes a necessary part of waste site planning where significant levels of organic residue are involved. Usually, gaseous air contaminants are not determined in routine site surveys during disposal, and certainly not after closure. Surveys, too often, only extend to liquid (leachate) sampling and analysis.

Gases evolve from landfills and impoundments and other burials as a result of:

- Vaporization of liquids
- Chemical reactions
- Biological activity
- Venting of entrained gases

Examples of gaseous emission range from organic decomposition gases (methane, hydrogen sulfide) from proteinaceous and plant wastes, to radon gas from uranium mill tailings, and to solvents (chloroform, benzene, and trichloroethane) from chemical process waste impoundments.¹¹ Malodorous emissions from liquid and sludge industrial wastes, notably sugar beet pulp, and chemical processing industries include methane, methylmercaptan, dimethyldisulfide, and hydrogen sulfide.¹¹ Covering of surface impoundments and landfills alone does not terminate gas production. Some means of channeling, collecting, and venting are necessary. Once the site is closed the only way to determine the necessary removal of the emissions is by thorough monitoring over the season of maximum generation.

Monitoring for possible gas emission through the surface cover should be made regularly, especially so if cracks appear. Gas wells with vents may be established for both preclosure and postclosure monitoring. Wyss et al.¹¹ presents a brief discussion of the mechanisms of gas emission upon closure of impoundments that can act as a guide for development of a monitoring program for gases. Surface impoundment-closure-key steps are presented in Figure 3 for reference. The alternatives that must be selected are presented schematically

for closure planning. As shown, gas flow is influenced by porosity, free space diffusivity, and degree of saturation. Monitoring procedures must be not only capable of evaluating the quantity, quality, and kinds of gases, but also the possibility of gas being absorbed and/or reacting with the soil water and leachate with the potentiality of contaminating the groundwater. Wells, therefore, must be established both above and below the disposal site in line with the underground water flow. The extent of well monitoring depends on the nature of the waste disposals, soil permeability, thickness of the soil liners and native soil, and depth to groundwater.

III. ODOR CONTROL

A. Origin and Nature

The one single environmental factor that is more responsible for odor generation from organic wastes is the supply of oxygen. Organic wastes tend to lose their unpleasant odors when the system is aerated and the decomposition changes from anaerobic to aerobic. Excessive inflow of air into organic waste burials results in:

1. Development of aerobic biodegradation that proceeds more rapidly than that under anaerobic conditions
2. Decrease and often complete elimination of methane and malodorous gases
3. Reduced BTU value of the gas
4. Increases in the risk of spontaneous combustion by rapid oxidation
5. Decreases in the risk of transport and accumulation of combustible gas in critical areas beyond the disposal site

The identification of a great variety of organic chemicals as assembled in Table 1 from animal and sewage disposal sources establishes the health hazardous nature of odors once believed to be only a nuisance. The malodorous compounds evolve from most animal and sewage waste. They are represented by those containing sulfur, reduced nitrogen, and carboxyl moieties.^{1,10-12} Different wastes emit characteristic odors that can be identified, although identification of a complete list is difficult.^{13,14} Some examples reported by Mosier et al.¹ include

1. Poultry rendering — aldehydes and small amounts of dialkyl sulfides
2. Dead stock, beef offal, and slaughterhouse trimmings — carbonyl compounds, traces of sulfurous and nitrogenous compounds
3. Fish meal — amines, triethylamine, putrescine
4. Feather cooking — acrolein, acetaldehyde, methyl mercaptans, diethylamine, *n*-propylamine, NH_3 , and H_2S
5. Kraftwood pulping — volatiles as H_2S , methylmercaptan, diethyl sulfide, and a host of others as given in Table 1.

B. Odor Detection and Movement

Odor acceptability lends itself poorly to quantitative chemical or physical measurements, although the intensity of an odor can be measured quantitatively for known compounds.¹² Legally, odors may be considered a nuisance, but it is a personal matter of being either acceptable or unacceptable. For example, the aerobic decomposing plant materials in a compost most often are described as “earthy”. Odor intensity and quality control acceptability at the source may be independent or counteractive, additive, or synergistic.¹⁵

The concepts of odor intensity, quality, and acceptability are involved in detection. Unfortunately, the only reliable detection mechanism is the preception of an odor or scent

through stimuli affecting the olfactory nerves. These nerves are highly sensitive and capable of detection within the range of parts per million and in highly specific instances within the ranges of parts per billion. Response to detection varies from person to person just as acceptance and unacceptance varies among people. An average person can detect three levels of intensity. People trained for odor panels can distinguish between five levels of intensity and select acceptable odor threshold values.

Movement of odors depends mainly on the vehicle of air transport. The air, of course, is constantly on the move. Diffusion also can be a factor of movement under very confined conditions, such as within the pores of soils, stones, block, rock, and brick. Since odors are highly diluted by the air and originate from specific identifiable chemical compounds, their movement, dispersion, and diffusion are closely tied to associated gases (which in themselves may represent different detectable odors).

C. Odor Control

The chemical nature of odors makes them susceptible to specific chemical reactions of adsorption, sorption, precipitation, and chemical combination. Odor control techniques center around well-known reactions. On the other hand, the most effective solution to odor problems is to change the waste-treatment design or source environment from anaerobic to aerobic. Other factors of the environment that determine the nature of the biological process (e.g., pH, temperature, red/ox, water, and nutrients) may also be manipulated. This may appear to be an easy solution. Unfortunately, manipulation of large volumes of organic wastes is not easy. In fact, it is so difficult, that the problem of odors remains largely unsolved both technically and economically.

D. Odor Monitoring

There are few direct approaches to odor problems. The subjective character of the physiological effects of odors is shown by its dependence on an individual's attitude, disposition, and even time of day.¹⁶ Odors from large organic disposals and industrial gases affect the economics of a community through diminishing tourism, tax revenues, payroll tax revenues, and growth and development. People also disagree as to odor acceptability depending on who is responsible for its origin and who is not, but downwind.

Odor control regulations differ geographically among the many state and local pollution control agencies as reported by Leonardos.¹⁷ None of the many regulations function ideally. In fact, the regulations fail to be satisfactory because of the lack of ability to measure odor intensity and quality objectively and reliably. Identification of a few of the least acceptable odors has been helpful in assessing the obnoxious and nuisance factor. These include mercaptans, sulfides, disulfides, amines, and aldehydes.¹⁸

Monitoring at burial sites, impoundments, lagoons, and ponds cannot by itself control odors. Unless the originator insists on good housekeeping habits of cleanliness, good material management, prompt cover procedure, and closed system techniques, no control or monitoring system can be effective. For example, injecting liquid sewage sludges into the soil instead of sprinkling on the surface eliminates the odor problem.

IV. AEROSOLS

A. Microbial Aerosols

Aerosols can be dispersed into the environment from all surface activities where systems are not closed. Soil injection is an exception. For example, both pathogenic and nonpathogenic microorganisms may evolve during many agricultural activities.¹ During sewage treatment processes, aerosol containing microorganisms also may be emitted. The distribution around sewage treatment operations depends largely on prevailing wind direction. Just as

with odors, concentrations and distance of travel are greatest downwind. Aerosols also may originate from large open impoundments and vary in emission depending on wind intensities. The greater the wind intensity, the greater the aerosol emission. Yet, under farm-field conditions, the oxidation ponds or ditches do not appear to contribute as significantly to aerosols as compared to the farm animals themselves.¹

B. Dust and Other Emissions

Airborne dust and chemical contaminants eventually end up on the land. Although the total amount is considerable, the natural distribution over wide areas allows the soil to biodegrade and ameliorate the potential adverse effects of toxic airborne pollutants as well as those of only nuisance quality.

In 1968, Wadleigh¹⁹ reported levels of airborne chemicals and dusts to be approximately:

1. 30 million tons of sulfur oxides (SO, SO₂) from shelters, use of fossil fuel for heat and power, and burned refuse
2. 75 million tons of other chemical contaminants from exhausts of internal combustion engines, industrial mills, refuse burning, home heating, forest fires, and agricultural burning
3. 17 million tons of dust are released into the atmosphere from cotton gins, alfalfa mills, lime kilns, cement plants, smelters, and mining operations
4. 30 million tons of dust of natural sources enters the atmosphere each year

The values for industrial constituents are expected to be no higher today (1984) than in 1968 due to more stringent control over air emissions.

The soil digests and incorporates all of the airborne waste into its system as a natural part of development in response to the environment. Acid air pollution can result in acid rain. The long time effect on soil-forming processes and the resultant soil profile is a matter of speculation and will differ geographically depending on climatic conditions. The soil-forming processes in humid regions may be expected to accelerate, whereas those in arid and semiarid regions probably will not be significantly affected for hundreds of years because of the natural lime (caliche) content of the soils and neutral to alkaline pH. In fact, additions of sulfuric acid (H₂SO₄) to arid land soils has been demonstrated as benefiting soil physical properties and crop production.²⁰

In addition to dust from industrial sources, atmospheric dust originates from wind erosion. Nearly all agricultural land tilled (22.3×10^6 ha or 55×10^6 a) is susceptible to wind erosion. Lesser amounts, but still significant, dust arises from highway and industrial construction sites. Soil modification procedures and soil conservation practices can reduce wind erosion and airborne dust pollution to acceptable levels, although recent highway fatalities in Arizona reminds us that the hazard of dust pollution has not been fully controlled. There remains far too much airborne dust in the atmosphere today, although wind erosion research and adopted practices since the "dust bowl" days has contributed importantly to effectiveness of airborne dust control.

V. SOIL FILTER-SCRUBBERS

A. Application

Soil filter-scrubbers (also called earth filters or soil filters) are designed to remove air pollutants of odor, gases, aerosols, and particulates. They are more in use in European disposal designs than in the U.S.^{2,3} Conventional removal techniques of malodorous gases from air, such as sorption, require energy input, costly maintenance, water, and high capital cost. Some of these techniques rely more on dilution rather than removal. Some yield hazardous waste collections of polluted water or lime slurries. Soil filters in certain cases can avoid these limitations.

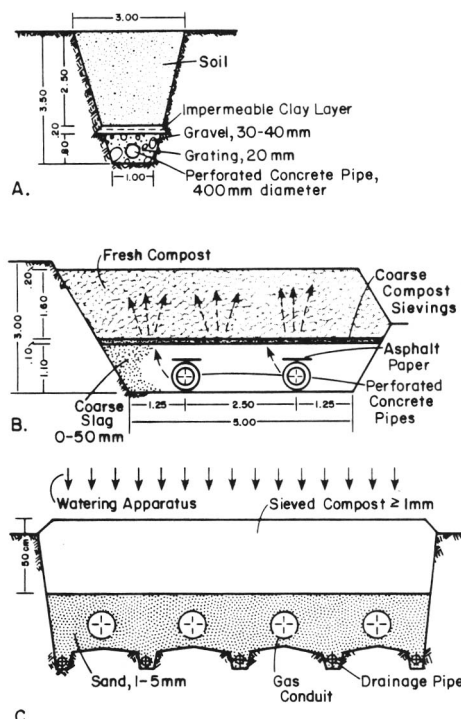


FIGURE 4. Cross section of earth filters. (A) Soil filter in Geneva, Switzerland; (B) compost filter in Duisburg, West Germany; and (C) Helmer's proposed compost filter. (From Bohn, H. L., *J. Environ. Qual.*, 1, 372, 1972. With permission.)

B. General Principles and Procedures for Use

The general principles and procedures for use of earth scrubbers are briefly described:²

Polluted air or gases are collected and blown through a perforated pipe that is buried in soil or organic plant material compost as illustrated in Figure 4. The soil or compost is relatively loosely packed to permit ready permeability and infiltration of gases. Gases, aerosols, and particulates adsorbed or collected on the soil or compost particulate surfaces may then be oxidized. Gases of NH_3 , SO_2 , H_2S , NO_x convert to their respective acids, nitric (H_2NO_3) and sulfuric (H_2SO_4), and innocuous gases of N_2 , CO_2 , and H_2O . The filters may be adapted to a wide range of conditions and a variety of gases and the vapor phase of toxic volatile solutions.

Earth filters clean up gas and odor pollutants in two major ways: (1) sorption and (2) oxidation to either relatively innocuous constituents or more easily managed substances. Earth filters continually regenerate themselves when used wholly for organic gases. Thus, ideally, soil filters can actually eliminate hazardous and/or toxic substances. Soil filters have application on both large and small installations.²¹ Should acid be one of the oxidation products of the gases, fine granular lime may be mixed into the soil or compost as a neutralizing agent since the sorption capacity is approximately equal to the base content of the filter.

Since earth filters most often depend on favorable microbial activity to function at a maximum, environmental conditions must be maintained at or as near optimum as practicable. The temperature, oxygen (air), and moisture conditions must be maintained at a favorable level and the medium must not be poisoned by overtreatment of excessively toxic substances and gases. Earth filters require periodic moisture additions to counter the drying effects of escaping gases.

Table 3
PERMEABILITY OF GAS THROUGH DRY SOILS AND
SOIL MATERIALS

Soil	Permeability (μm^2)	Soil Material	Permeability (μm^2)
Cave loam	2.8	Loamy sand	5.6
Edina silt loam	4.0	Fine sand	56.0
Sonoita sandy loam	4.7	Coarse sand	240.0
Karro loam	16.0	Calcic soil	
Stewart clay loam	30.0	0.2—0.4 mm fraction	44.0
Webster silt loam	44.0	0.1—1.0 mm fraction	220.0
		1.0—2.0 mm fraction	2300.0

From Bohn, H. L., *Soils for Management of Organic Wastes and Waste Waters*, Elliot, L. F. and Stevenson, F. J., Eds., American Society of Agronomy, Madison, Wis., 1977, 607. With permission.

The Geneva filter shown in Figure 4A operated for over 10 years without interruption. The perforated concrete pipe is 36 m long, is buried 3 m deep, and flows air at 300 m³/h at 100 to 200 cm of water pressure.² The Duisberg-Huckingen compost filter (Figure 4B) has a higher microbial content and air flow than the soil filter. Compost filters, however, develop such large masses of microbial tissues (fungi and active mycetes) that air flow has a tendency to excessively channel resulting in poorer adsorption and less efficient oxidation than soil filters.

The use of soil filters for highly toxic and slowly degradable gases and air particulates, requires such long resident time as to be impractical. Designs to use soils to treat malodorous gases requires the determination of:

- Chemical and adsorption reaction rates
- Sources of acceptable soil
- Extent of odor removal
- Cost
- Ultimate disposal

Several physical effects also should be addressed for the design of soil filters:³

- Particulate collection
- Moisture content of the filter
- Temperature
- Residence time
- Gas flow in soils
- Gas distribution system in filter
- Power demand

C. Biochemical and Biological Aspects

A number of chemical and microbiological characteristics of soil filter scrubbers must be considered in any gas and odor cleaning design. The microbiological aspects and needs of the organisms are universal to any biodegrading organic system where a wide variety of organic wastes are involved.

According to Bohn, biological oxidation rate in soil filter scrubbers is relatively slow compared with strictly chemical reactions.³ The oxygen/oxidizable gas ratio should be maintained at a minimum of about 100 on a mass or volume basis. Generally the design requirement of soil filter systems exceeds this value by a wide margin. Oxidation rates change with time depending on the nature of the malodorous gases and presence of highly toxic emissions. For example, the removal rate of mercaptan (CH_3SH) increases slowly over 6 weeks. Butanol, in contrast, decreases from 500 to a steady rate of about 100 mg of butanol per kilogram of compost.²²

Continued use of the soil filter requires addition of fine granular limestone when acids represent the end-product of biological oxidation. Usually nitrogen replenishment is not needed, but Schwendinger²⁴ claims that increasing the natural soil fertility increases the rate of hydrocarbon breakdown. One should keep in mind, however, that volatile aliphatic gases react slowly with the soil and biodegrade slowly to the extent they lend themselves poorly to retention and removal in this system where gas flow allows for very low residence time. The unsaturated hydrocarbons such as ethylene and acetylene react with the soil and biodegrade much more rapidly than the saturated hydrocarbons.^{24,25} In the same category with the slow reactors are CO_2 and CO gases. More rapid reacting gases are represented by the carbon-hydrogen-oxygen (C-H-O), acetoin ($\text{H}_3\text{C-CO-CHOH-CH}_3$), and organonitrogen compounds, e.g., putrescine ($\text{H}_2\text{N-}[\text{CH}_2]\text{-NH}_2$), cadaverine ($\text{H}_2\text{N-}[\text{CH}_2]_5\text{-NH}_2$), and cyanides (CN-). Organosulfur gases of CH_3SH structures and inorganic H_2S are absorbed and readily oxidized. CS_2 , on the other hand, reacts slowly and oxidizes slowly in soil filters.³ Organohalogens require more residence time with the soil microorganisms than is generally available in soil filter scrubbers.^{26,27} Pentachlorophenol (PCP) is readily oxidized at levels of 30 ppm as microbial populations build up, but soil filters allow too short a time for high efficiency.^{25,26}

D. Physical Aspects

Most problems, associated with soil filters, center around the selection of soil with a suitable particle size and structure for efficient odor absorption. Coarse sandy soils have less capacity to absorb odors and require replacing more frequently than soils of finer particle sizes. On the other hand, soils high in clay content, that have the greatest capacity to absorb gases, usually have lower gas flux and plug more readily than those high in coarse sand. Medium-textured soils appear to be most effective in absorption. Air, like water, moves through soils depending on the nature of the structure. According to Elgabaly and Elghamry,²⁷ gas permeability may be independent of the particle size, among the medium-textured soils, as shown in Table 3. Soil structure dominates the flow relationships in these cases. The resistance to gas flow decreases with the fourth power of increasing pore diameter in uniform-sized pores. Gas, therefore, flows primarily through the larger soil pores. Inhibition of flow occurs mostly as a result of filling of the larger pores as the water content becomes appreciable and blocks gas entrances. Soils that crack readily upon drying also are least efficient in gas and odor absorption. Finer-textured soils are more susceptible to cracking. Both extremes of soil texture have limitations, with the least problems associated with medium to coarse textured soils. When tube or pipe designs are used, a gravel envelope is necessary to overcome the resistance of the surrounding soil to gas flow out into the soil absorption area.

REFERENCES

1. **Mosier, A. R., Morrison, S. M., and Elmund, G. K.**, Odors and emissions from organic wastes, in *Soil for Management of Organic Wastes and Waste Waters*, Elliott, L. F. and Stevenson, F. J., Eds., American Society of Agronomy, Madison, Wis., 1977, 531.
2. **Bohn, H. L.**, Soil absorption of air pollutants, *J. Environ. Qual.*, 1, 372, 1972.
3. **Bohn, H. L.**, Soil treatment of organic waste gases, in *Soils for Management of Organic Wastes and Waste Waters*, Elliott, L. F. and Stevenson, F. J., Eds., American Society of Agronomy, Madison, Wis., 1977, 607.
4. **Blanchet, M. J. and Staff**, Treatment and Utilization of Landfill Gas: Mountain View Project Feasibility Study, EPA SW-583, Office of Solid Waste, U.S. Environmental Protection Agency, and Pacific Gas and Electric Co., San Francisco, MERL, Cincinnati, Ohio, 1977, 115.
5. **Merz, R. C. and Stone, R.**, Special Studies of a Sanitary Landfill, U.S. Department of Health, Education and Welfare, Washington, D.C., NTIS, Springfield, Va., PB-196, 148, 240, 1970.
6. **Hillel, D.**, *Introduction to Soil Physics*, Academic Press, New York, 1982, 142.
7. **Lutton, R. J., Regan, G. L., and Jones, L. W.**, Design and Construction of Covers for Solid Waste Landfills, Sect. 9, U.S. EPA-600/2-79-165, U.S. Environmental Protection Agency, ORD, Cincinnati, Ohio, 1979, 121.
8. **Rogoshewski, B. J. and Wetzel, R. S.**, Handbook for remedial action at waste disposal sites, in *Land Disposal of Hazardous Waste*, Shultz, D., Ed., Proc. 8th Annu. Res. Symp., EPA-600/9-82-002, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1982, 512.
9. **Landreth, R. E. and Rogers, C. J.**, Promising Technologies for Treatment of Hazardous Wastes, Rep. No. EPA-670/2-74-088, U.S. Environmental Protection Agency, Washington, D.C., 1974, 37.
10. U.S. Environmental Protection Agency, Handbook for Remedial Action at Waste Disposal Sites, EPA-625/6-82-006, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1982, 497.
11. **Wyss, A. W., Willard, H. K., Evans, R. M., Schmitt, R. J., Sherman, R. G., Bruehe, D. H., and Greco, E. M.**, Closure of Hazardous Waste Surface Impoundments, EPA SW-873, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1980, 92.
12. **Miner, J. R.**, Odors from Livestock Production, Agric. Engineering Department, Oregon State University, Corvallis, 1973, 127.
13. **Mosier, A. R., Andre, C. E., and Vietz, F. G., Jr.**, Identification of aliphatic amines volatilized from cattle feedyards, *Environ. Sci. Technol.*, 7, 642, 1973.
14. **Rains, B. A., De Primo, M. J., and Groseclose, I. L.**, Odors Emitted from Raw and Digested Sewage Sludge, U.S. EPA-670/2-73-098, U.S. Environmental Protection Agency, Washington, D.C., 1973, 45.
15. **Sullivan, R. H., Cohn, M. M., and Baxter, S. S.**, Survey of Facilities Using Land Application of Wastewater, U.S. EPA-430/9-73-006, U.S. Environmental Protection Agency, OWPO, Washington, D.C., 1977, 377.
16. **Petri, H.**, The effect of hydrogen sulfide and carbon disulfide, *Staub*, 21, 64, 1961.
17. **Leonardos, G.**, A critical review of regulations for the control of odors, *J. Air Pollut. Control Assoc.*, 24, 456, 1974.
18. **Morecreeff, R. W.**, *Odor Preferences*, John Wiley & Sons, New York, 1966, 89.
19. **Wadleigh, C. H.**, Wastes in Relation to Agriculture and Forestry, Misc. Publ. No. 1065, U.S. Department of Agriculture, U.S. Government Printing Office, Washington, D.C., 1968, chap. 1.
20. **Stroehlein, J. L.**, pH control on alkali soils, *Solutions*, 81, 1980.
21. **Miyamoto, S. and Stroehlein, J. L.**, Improving water penetration in some Arizona soils — sulfuric acid, *Prog. Agric. Ariz. Coll. Agric.*, 27, 13, 1975.
22. **Miyamoto, S., Warrick, A. W., and Prather, R. J.**, Land disposal of gases. III. Sorption patterns from buried gas injection pipes, *J. Environ. Qual.*, 3, 161, 1974.
23. **Helmer, R.**, Sorption und mikrobieller Abbau in Bodenfiltern bei der Desodorisierung von Luftströmen. Stuttgarter Berichte für Siedlungswasserwirtschaft 49, Inst. für Siedlungswasserbau und Wassergutewirtschaft, 7 Stuttgart-Busnau, Band 1, West Germany, 1972.
24. **Schwendinger, R. B.**, Reclamation of soils contaminated by oil, *J. Inst. Pet.*, 54, 181, 1968.
25. **Abeles, F. B., Craker, L. E., Florence, L. E., and Leather, G. R.**, Fate of air pollutants: removal of ethylene, sulfur dioxide and nitrogen dioxide by soil. *Science*, 173, 914, 1971.
26. **Watanabe, I.**, Isolation of pentachlorophenol decomposing bacteria in soil, *Soil Sci. Plant Nutr.*, 19, 109, 1973.
27. **Elgabaly, M. M. and Elghamry, W. M.**, Air permeability as related to particle size and bulk density in sand systems, *Soil Sci.*, 110, 10, 1970.



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

Predicting Pollutant Transformations and Mobility



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

Chapter 4

SCREENING PROTOCOL FOR PREDICTING WASTE TREATABILITY

I. SCOPE

A. Disposal Controls

The unfavorable consequences of improper disposal of wastes at all levels of concentrations in the air, land, and water are more visible than in any period of history of our nation. Hazardous waste is not only being generated in larger quantities, but the toxic quality is worsening as new chemicals appear in the marketplace. Improper disposals of waste have been identified with contamination of air, land (soil, surface, and groundwater), streams, lakes, and oceans and finally food chains. The U.S. Government has found it necessary to divert 1.6 billion dollars into a "Superfund" to protect the environment in a few "worst" cases. The amount of wastes being generated as estimated in 1982 were¹

1. 60 million annual metric tons of hazardous waste
2. 33 million annual metric tons of municipal waste located in 18,500 sites covering 202,500 ha
3. 5 million annual metric tons of municipal wastewater treatment sludge (this amount will double by 1990 due to the higher treatment levels.)
4. 120+ million annual metric tons of flue gas cleaning sludges by 1985
5. Billions of tons of agricultural and mining wastes

Federal and state regulatory agencies have responded to the negative environmental impacts of improper disposals of solid and hazardous wastes, by requiring strict disposal controls. The controls cover waste generation and continue through site closure or "safe" disposal.

Legislation enacted by Congress includes the Resource Conservation and Recovery Act (RCRA) of 1976 and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 or "Superfund". RCRA deals mainly with the regulation of active facilities engaged in the storage, transportation, treatment, and/or disposal of hazardous wastes. CERCLA "Superfund" provides a mechanism and funding for the cleanup of abandoned hazardous waste sites that are polluting the environment and are threatening public health and safety. Both require specific methods for determining or demonstrating the treatability of a particular waste. Such methods would be invaluable to the Office of Soil Waste in implementing, and to operators in responding to, provisions in these regulations. Rate reactions also would be very helpful in selecting the most suitable method of disposal and assist in selecting acceptable sites for disposals. Land treatment is one of the attractive options being studied for acceptable disposal of hazardous wastes. Natural microbial decomposition processes most favorable for degradation and detoxification of waste materials must be established for all climates and as a condition for the selection of this option.

B. Purpose

The purpose of this chapter is to report a search of the literature that can provide a data base for selecting methods to use in predicting the treatability of solid hazardous wastes in soils. A screening protocol should involve a study of several short-term, reliable, noncomplex, and relatively inexpensive tests selected or adopted from currently available methods. The methods should result not only in evaluating the susceptibility to degrade, attenuate, adsorb, or otherwise render innocuous those wastes being disposed on or in the soil, but in identifying possible residuals and remnants of biodegradation of a toxic nature in order to

determine when a waste can be optimally reapplied or when plantings of economic crops can be made. Successful disposal of hazardous wastes on land or by land treatment depends primarily on their ready biodegradation without leaving toxic remnants and residuals available to enter the food chain or drinking waters. The main goal here then is to establish the ability to predict

1. Biodegradation rates of organic constituents
2. Attenuation of inorganics, particularly heavy metals
3. Pollutant movement through soil and soil materials in land application operations including surface incorporation, burials, impoundments, and ponds

C. Generating Data for Predictions

Functional predictions for land applications are not beyond reality. For example, models of the transport of certain trace and heavy metals, contained in municipal solid waste (MSW) leachates through soils, have been developed.²⁻¹⁰ The soil scientist also has demonstrated the potential for predictions:

1. Of solubility and plant availability of nutrient elements in agricultural soils
2. Of salt movement in soil reclamation
3. Of soil salinity and alkalinity control¹¹⁻¹⁵

Unfortunately, direct application of these studies to predict transport rates, for example, of heavy metals, organic solvents, oils, and other toxic chemicals in industrial hazardous wastes, through soils to underground water sources and food chains, cannot be made at this time. Without a complete knowledge of soil attenuation, biodegradation rates, transport rates, and stabilization mechanisms of pollutants, the full protection of our food chain and groundwater is not possible.

Generating new data necessary for predicting the fate and transport of hazardous industrial and commercial wastes in soils, and identifying the degree of treatment necessary to prevent transport to the groundwater, require the understanding of a complicated transport system. Unlike aqueous municipal land fill leachates, the vehicle of transport varies with the nature of disposals, which include a host of solutions and solvents, both miscible and nonmiscible with water. Not only the pollutant itself, but pollutant transport must be determined; for example,

1. In aqueous solutions alone
2. In aqueous solutions containing water-soluble solvents, such as alcohols and acetones
3. In aqueous solutions mixed with nonmiscible solvents such as certain aromatic hydrocarbons, petroleum oils
4. In aqueous solutions containing high concentrations of inorganic and organic salts, acids, and alkalies

Moreover, industrial solid wastes characteristically contain high levels of soluble inorganic and/or organic constituents as compared to those found in natural soil and soil solution, MSW, and other landfill type leachates.

D. Previous Work

Industrial solid and hazardous waste sources involve

1. A broader spectrum of metals than plant nutrients
2. A much higher concentration of organics than is in municipal solid waste leachates

3. A wider diversity of solvents and solutions or leachates than is usually present in the natural soil solution where plants thrive
4. A high concentration of organic solvents, such as xylene, toluene, phenols, chlorinated hydrocarbons (such as TCE, PCP), and petroleum oils with associated heavy metals and solvent products

On the other hand, certain basic principles of metal migration or attenuation in soil found with the relatively dilute MSW leachates and rainwater can be useful for predicting trends and can aid in developing models of transport of pollutants in land treatment investigations.¹⁶⁻¹⁹ Obviously, a knowledge of biodegradation rates and pollutant transport in, or associated with, nonaqueous solvents must be developed primarily from new research.

Before predictive designs for land applications and burials of hazardous wastes can be established, a multitude of factors influencing all pollutant transport in soils must be identified and evaluated. For example, the three prominent components of the disposal environment affecting pollutant migration — the transport system or liquid carrying the pollutant, the porous medium through which the constituent is being transported, and the potential polluting constituent(s) — must be characterized in detail. The principal soil physical and chemical characteristics found to influence attenuation of metals in soils are

Physical Properties

- Texture (sand, silt, and clay)
- Structure (particle arrangement)
- Stratifications (layers of different textures)
- Compaction
- Restrictive layers (lime, silica, and Fe and clay pans)
- Hydraulic conductivity (or permeability)

Chemically Related Properties

- Surface area of soil particles
- Clay mineral type
- pH level
- Total dissolved solids (inorganic salts)
- Hydrous oxides of Fe, Al, and Mn
- Cation exchange capacity

The primary physical soil characteristic influencing the rate of biodegradation and reactivity is surface area of the soil particles. For example, clay has many times the surface area of sand, per unit weight. Clay also is the most important particle size for attenuation and is the primary seat of chemical, biological, and physical reactions in soils.

Leachates — The dilute aqueous leachate characteristics that have been found to prominently influence attenuation of metals in soils are^{18,19}

1. Total organic carbon content (TOC)
2. Total dissolved solids (TDS), inorganic salts as measured by electrical conductivity (EC)
3. pH (acidity and alkalinity)
4. Pollutant constituent concentrations (metal or organic constituent to be studied)
5. Soluble Fe, Mn, and Al
6. Volume of leachate passing through soil
7. Age of leachate
8. Aqueous or organic solvent content

There is reason to believe that most, if not all, of these same characteristics will influence transport and fate of polluting chemicals and solvents as they do with the solid MSW

leachates. Undoubtedly, the intensity and interaction of these characteristics or variables will not be identical in different systems. Their effect in influencing pollutant migration rates through the soil, as a threat to the quality of underground water sources, requires intensive research to obtain data of a quantitative nature to form a sound base for predictive model development. Hopefully, the models developed for migration of metal from dilute aqueous leachates through soils may serve as a guide for other pollutant transport from industrial and commercial sources. These include, for example, those patterned after the Error Function¹⁹ and Lapidus-Amundson equations.^{2,20,21} Already, trichloroethylene, toluene, xylene, and other organic solvents are polluting underground water sources in and about the metropolitan areas of cities and virtually nothing is known about the way they biodegrade, react, or migrate through soils.^{22,23}

The land treatability of a liquid hazardous waste in the soil may depend as much on the length of time it resides in contact with the active soil microflora, concentrated in the surface or A horizon, as with its susceptibility to attack. Soil permeability, therefore, as influenced by the nature of the liquid, may justifiably become one of the tests or a part of a test of treatability for liquids. Some organic solvents appear to enhance the soil permeability manyfold, reducing the resident time for biodegradation and/or detoxification of the pollutants to ineffectual levels.^{24,25} Failure of clay and natural soil liners to act as barriers for the protection of groundwaters have been attributed to the presence of certain organic solvents.²⁶

II. SCREENING TESTS AND PILOT EXPERIMENTS

A. Requirements of the Test

A number of short-term, reliable, noncomplex, and reasonably inexpensive tests useful for predicting hazardous constituent fate and transport and fate and degree of treatment may be suggested from available information in the literature. These tests can aid in the design of the more comprehensive experiments such as land treatment/utilization under field conditions as a first step in developing the screening protocol. These tests also can be used as a data base for the development of new and more effective and efficient methodologies. At this point in time, however, it is believed that considerably more research development is necessary before a single test can be made available to provide all of the information needed for predicting waste treatability and soil-site interactions with any degree of confidence. At present, it appears that several tests in conjunction with a given waste and site must be employed to arrive at sufficient data to form a sound base for predictive purposes.

B. Controlled Laboratory Tests vs. Natural Field Tests

Test methods have been oriented primarily toward the laboratory for several important reasons:

1. Short-term, reliable, noncomplex methods are most desirable. Field-based experiments do not lend themselves to these types of test methods.
2. *In situ* field tests are both too time consuming and expensive to be practical at this point in time.
3. *In situ* field soils are highly heterogeneous. Gross natural variations occur, such as texture, stratifications, cracks, restrictive subsoil layers, excessive compaction, root and rodent channels, and pipings. Therefore, a great number of tests usually are required to arrive at acceptable answers.
4. Reliable field tests cannot be undertaken unless an abundant source of trained manpower is available.
5. Climatic and microclimatic conditions (moisture, temperature, and wind) usually are highly variable under field conditions and less controllable than in the laboratory or greenhouse.

Laboratory model results should not be extrapolated and projected directly into the site disposal design without some modifications as indicated by actual field verification and common sense. Bench-scale data, however, are valuable and some positive decisions may be based on the results. Not all of the suggested screening methods listed in Table 1 need to be undertaken at a specific site and for all wastes. Selection of methods must be made on a case-by-case basis since no two cases are likely to be the same. The screening methods suggested may be used with caution for predictive purposes and for the establishment of guidelines on

1. Land treatability of wastes
2. Loading rates and total allowable loading rates
3. Ultimate fate of wastes
4. Assimilative capacity of soils for waste constituents
5. Acceptable facility management and optimum operating conditions
6. Size and extent of the site
7. Kind of disposal design that best accommodates the kind of waste requiring disposal
8. Monitoring design which will provide advance warning of possible pollutant contamination of above and below ground environment

III. SPECIFIC METHODS

The first demand is for information on the level of toxicity of the hazardous industrial waste when first added to, or mixed into, soil at different concentrations or loading rates. The second demand is to determine how long the inhibition exists, if any, for microorganisms and plants. The third demand is to determine the rate of waste biodegradation. Test soils treated with different concentrations of the hazardous waste and having different periods of incubation time must be available at all times and in sufficient quantity for use in evaluating the effectiveness of the various short-term tests. Three modes of test soils should be developed:

1. Moist untreated reference soils
2. Waste-treated soils in bulk containers also held in constant temperature rooms or labs
3. Small field plots of both waste-treated and untreated soils

A. Soil Sampling

When the specific site location is known, soils representative of the site facility may be obtained for testing at different depths, depending on method of intended waste disposal or waste treatment.

Reference soils should be established that represent the land disposal area. Such standards then can be used in conjunction with the soils to be tested and thereby act as references for comparative purposes for future site selection. The soils to be tested should be taken from the area being considered for disposal. If, for example, surface disposal is proposed, surface soils at 30-cm intervals should be taken to a depth of at least 5 m. Soil representative of the bottom and sides of the excavations for landfills and other burials should be obtained as well as greater depth samples.

Selection of soils for the various methods and laboratory characterization may be accomplished as follows.

Sample location — Sampling depends on (1) final site selection, (2) type of disposal (e.g., surface or subsurface), and (3) solid or liquid wastes or involvement of both. The deepest and most uniform soils should be selected for a site. The samples should be taken then that adequately represent the disposal area.

Table 1
SELECTED WASTE TEST METHODS FOR APPRAISING TREATABILITY OF WASTES AND WASTE-SITE INTERACTIONS

Test	Method	Tolerance diagnosis and evaluation
I. Biological		
A. Microbiological (laboratory)		
1. Standard dilution-plating technique: for microbial populations		a. Microbial compatibility b. Microbial toxicity c. Biodegradation of organics
2. Respirometry: CO ₂ -evolution		a. Biodegradation of organics b. Microbial toxicity c. Microbial compatibility
3. Toxicity reduction: Microtox [®] , Beckman Co., Inc.		a. Specific microbial toxicity b. Microbial compatibility c. Biodegradation of organics
4. Dehydrogenase activity: Frankenberger & Johnson (1982)		a. Microbial toxicity b. Microbial compatibility c. Biodegradation of organics
5. Soil-enrichment and extraction and respirometry		a. Biodegradation of organics b. Microbial toxicity c. Microbial compatibility
6. Microbiological mutagenicity assay: Brown et al. (1980)		a. Chronic toxicity b. Biodegradation of organics
B. Plant (Growth chamber)		
1. Seed germination: soil and soil extracts		a. Phytotoxicity b. Germination
2. Seedling establishment: Stanford-DeMent Short-Term (19)		a. Phytotoxicity b. Plant Growth c. Diagnostic pollutant
3. Root mat technique Dean-Glendhill (1956)		a. Phytotoxicity b. Root growth c. Diagnostic pollutant conc
(Greenhouse)		a. Phytotoxicity b. Diagnose mineral excesses c. 50% growth decrement

(Field plots)	1. Field-plot technique (verification of bench scale methods)	<ul style="list-style-type: none"> a. Verification of laboratory tests b. Phytotoxicity c. 50% growth decrement d. Diagnose mineral excesses e. Degradation of waste a. Pollutant movement/attenuation b. Leachate quality c. Phytotoxicity d. Degradation of waste
	Lysimeter leaching	
(Lysimeter)		
II. Chemical (Laboratory)	1. Soil column	<ul style="list-style-type: none"> a. Metal attenuation b. Breakthrough curves for model data c. Movement evaluation d. Desorption evaluation e. Permeability and infiltration rate of pollutants a. Metal attenuation b. Adsorption, sorption, cation exchange capacity
	2. Batch study	
	3. Soil thin-layer chromatography	<ul style="list-style-type: none"> a. Metal attenuation b. Sorption, adsorption
	4. Waste residue analyses	
	5. Soil chemical analyses	<ul style="list-style-type: none"> a. Nondegradable residues a. pH b. Electrical conductivity c. Cation exchange capacity d. Free iron oxides a. Particle size distribution b. Soil surface area c. Bulk density d. Effective porosity a. Data for design specifications b. Quality control data during construction c. Data for chemical compatibility of clay soils d. Determine soil failure such as see page velocity
	1. Soil physical analysis	
III. Physical (Laboratory)		
	2. Permeability	

Table 1 (continued)
SELECTED WASTE TEST METHODS FOR APPRAISING TREATABILITY OF WASTES AND WASTE-SITE INTERACTIONS

Test	Method	Tolerance diagnosis and evaluation
(Field, <i>in situ</i>)	1. Permeability- <i>in situ</i> field tests 2. Hydraulic conductivity	Data for design specifications Liquid flux: saturated hydraulic conductivity 1×10^{-7} cm/sec
IV. Volatilization (Environmental chamber)	1. Environmental chamber volatilization 2. Field-air studies	a. Evaporative transfer from free liquid surface of different compositions b. face of different compositions c. Temperature, air flow rate d. Soil moisture levels Application method and loading rates
V. Soil erosion (Field plot)	1. Water erosion-runoff rain simulation 2. Wind erosion-simulation	a. Soil erodibility: universal soil loss equation a. Wind erodibility: wind erosion equation

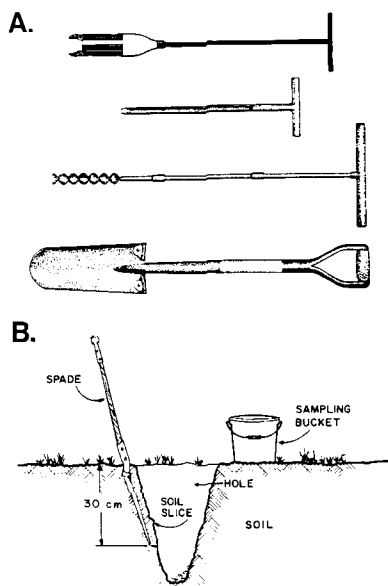


FIGURE 1. How to take a soil sample.
(A) Soil sampling equipment; (B) sampling
for surface soils.

Surface disposals — Samples for surface disposal may be taken from a grid system, as few as 2 or 3/ha, to a depth of 5 m if the soil is homogeneous and no variable textures or concentrations (lime, gypsum, clay pan, or iron pans) are present. If the soil is heterogeneous, highly variable in texture, supports shallow water tables, or encompasses aquifers, then samples at more frequent intervals should be taken to the depth of expected water penetration. The object is to fully characterize the soil profile. Figure 1 illustrates simple hand tools for sampling surface soils of land treatments.

Subsurface disposals — Soil samples should be taken at greater depth for excavated disposal sites. For example, if a disposal is to be 10 m deep (30 ft), enough samples from the 0- to 10-m depth should be taken to characterize the soil material for lateral as well as vertical flow. The number taken, again, depends on the soil homogeneity of the whole site. Sampling below 10 m should begin by taking cores at greater but regular intervals (e.g., 1 or 2 m) until the static underground water table or bedrock is contacted.

Size of soil sample — A 5×10 cm column of soil requires a minimum of 1 kg of material, therefore, a total of 3 to 6 kg (6 to 12 lb) of soil (on an air-dry basis) is needed to satisfy both the analytical and soil treatability tests. The minimum number of soil columns for a single test is three. Other methods will require different amounts of soil depending on replications and objectives of the method. For example, premonitoring should be more comprehensive than at any other stage in the establishment of the waste site facility.

B. Chemical Analyses

Free iron oxides of the soils are determined by the method of Kilmer,²⁷ surface area by the method of Heilman et al.,²⁸ using the ethylene glycol monoethyl ether technique, and manganese by a modified procedure of Bernas.²⁹ For total analysis, a sample size of 1 g of finely ball-milled soil, 10 ml of *aqua regia*, and 6 ml of HF are used for digestion. Boric acid (2.0 g) then is added and the sample is diluted to a final volume of 50 ml. The pH values are measured using the glass electrode. Where pH, common ions, total dissolved solids (EC), and cation exchange capacity are evaluated, the methods recommended by the American Society of Agronomy are used.³⁰

Al, Fe, and Mn contained in the leachates, other liquids, and effluents are measured by atomic absorption spectrophotometry using standard procedures recommended by the company supplying the equipment such as, Jarrell-Ash or Perkin-Elmer. Chemical interferences are minimized by matrix adjustment using La and K according to Ando et al.³¹ Using the dual channel of the AA with one channel carrying a hydrogen continuum lamp, the extent of background for Cd is evaluated. In diluted leachate, background corrections are found not to be required because of the comparatively low level of interferences. All samples are collected in the presence of redistilled HNO₃ to give a final pH of 2. The Ca, Mg, K, and Na are measured by flame emission³² and NH₄-N, P, and Si are measured according to the standard methods of the APHA-AWWA-WPCF water and waste water methods.^{33,34} Total organic carbon (TOC) is determined, for example, by a Beckman 915 A Model Total Organic Carbon Analyzer.

C. Physical Analyses

Standard X-ray — The relative amounts of secondary clay mineral types are determined by the standard X-ray technique.³⁵

Mechanical analysis — The procedure by Day³⁶ is used to identify the <2 μm clay minerals, silt (0.002 to 0.05 mm), and sand (0.05 to 1.00 mm) distribution of the soils.

Soil bulk density — Soil bulk density, ρ_b (g/cm³), is described in Chapter 1, part 1 and elsewhere.³⁷ For laboratory columns, the bulk density is calculated by dividing the oven-dried mass of the soil packed in the column by the volume of the column.

Soil particle density — Soil particle density, ρ_p (g/cm³), is defined as the ratio of the mass of the soil dried at 105°C to that of the volume of the solid particles as described in Chapter 1.

Soil porosity — Soil porosity, f (unitless), is the ratio of the volume of pores to that of the apparent volume of pores. Soil porosity can be related to bulk density and particle density by

$$f = 1 - \rho_p / \rho_p$$

The porosities of laboratory soil columns are determined using this equation.

Pore volume — For a given bulk volume of soil, the volume of pores is the porosity multiplied by that bulk volume. For laboratory columns, pore volume is calculated by multiplying the column porosity by the column volume. By convention, the volume of pores or pore volume of a column is taken as one unit and used as a basic unit for expressing influent or effluent volumes as “pore volumes”. For example, five pore volumes (PV) of effluent would be equal to five times the volume of pores in the column (or soil profile) under consideration.

Pore size distribution — Methods of evaluation are in Chapter 1 and elsewhere.^{38,39} Pore size distribution may be classified into macropores and micropores, where aggregates are distinct and water stable. The macropore class represents predominantly interaggregate cavities and micropore class, intraaggregate cavities. Air and water primarily migrate between aggregates or peds in the macropores and within aggregates in micropores. This separation can be useful in attempts to explain pollutant-attenuation discrepancies between soils of similar textural classes. Permeability as related to clay mineral type and amount of clay varies greatly depending on the dominance of one class over the other.

D. Microbial Population and Biodegradation

Biodegradation rate of organic constituents in wastes and wastewaters may be evaluated by several supporting methods. The rate of decomposition centers around three major properties of the organic constituents in land disposals, namely,

1. The availability of the carbon compounds for microbial attack
2. The degree of toxicity to the natural flora
3. Ability of the microflora to recover from the presence of toxic substances and degrade the organic carbon constituents by the development of a more tolerant population

In the first instance (1), toxicity is not a factor, an organic constituent may be readily, moderately, or slowly attacked, depending on its chemical and physical make-up. Some organics may be so slowly attacked that they remain without detectable alteration for long periods of time. In the latter instance, the constituent usually is highly insoluble and unreactive with its surrounding chemical and physical environment. In case 2, the degree of toxicity and concentration varies greatly with different constituents. The most toxic organic substance may completely eliminate the soil micropopulation rendering the soil nearly sterile, a condition from which it never recovers as long as the toxic substance is present even at very low concentrations. Acute toxicity should not be confused with chronic toxicity. The latter refers to highly hazardous genotoxic compounds of mutagenic, carcinogenic, or teratogenic nature and may be identified by the microbiological mutagenicity assay.²⁴

Should the waste-loading rates inhibit the microbial activity at the application rate first attempted in any of the methods suggested, several adjustments may be made, such as:

- Reduce the amount of waste applied
- Physically pretreat to improve pore space for better aeration
- Chemically pretreat by mixing with lime, woodchips, sawdust, etc.

1. Dilution Plating Technique

Soil treated with selected wastes and untreated control soils are analyzed by the dilution plating technique for bacteria, actinomycetes, and fungi according to the standard procedures commonly used by soil microbiologists. It may be necessary to add the selected wastes at graduated rates ranging from 0.001 through 10% to soils before incubation for 7 days to obtain the most desirable test materials.

Plate counts of the soil microorganisms are determined before and after soil treatments. This is accomplished by removing 10 g of soil and suspending it in a 90-mℓ water blank to obtain a 1:10 dilution. The serial dilution is continued until a 1:10⁶ dilution is achieved. Aliquots (1 mℓ) of the serial dilutions are cultured in triplicate on selective media, and colony forming units (CFUs) are determined by plate colony enumeration after incubation for 6 to 10 days at 28°C. The specific media will vary with the individual and location. For example, soil extract agar is not suitable from soils in arid lands that contain appreciable soluble salts.

Bacteria, fungi, and actinomycetes may be enumerated by the dilution plate method using any or all of the following media depending on the extent of information needed to identify the various groups of organisms.

Nutrient agar — Beef extract, 3 g; peptone, 5 g; and agar, 15 g, in 1 ℓ of water at pH 6.8.

Potato-glucose agar — Potato slices, 200 g; glucose, 20 g; and agar, 15 g. The potato slices are placed in 500 mℓ of water and autoclaved for 40 min. The extract is clarified by filtration and diluted to 1000 mℓ with water. The agar and sugar are then added.

Soil extract — To 1000 g of fertile soil add 1 ℓ of water and autoclave for 20 min. Add approximately 0.5 g of CaCO₃ to flocculate colloidal material and filter to clarify. Actinomycetes are best found with this medium.

Rose bengal-streptomycin agar — Glucose, 10 g; peptone, 5 g; KH₂PO₄, 1 g; MgSO₄·7H₂O, 0.5 g; and agar, 15 g, are added in 1 ℓ of water. Add 33 mg of rose bengal. Adjust pH to 3.8 with 0.1 N H₂SO₄ aseptically when the plates are ready to pour and after sterilization.

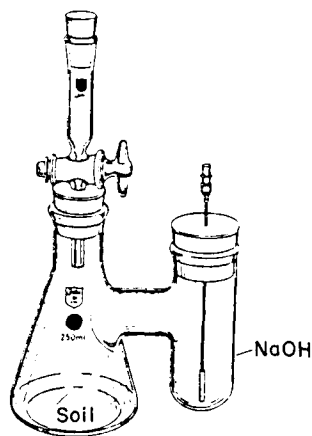


FIGURE 2. Assembly of a biometric flask for CO_2 -evolution measurement by soil microorganisms. (From Pramer, D. and Bartha, R., *Soil Sci.*, 100, 1, 1965. With permission.)

Also add the streptomycin when the agar is ready to pour. This medium is specific for soil fungi.

2. *Respirometry*

The respirometer method is used to evaluate microbial activity. The CO_2 evolved from 100 g soil alone and with various treatments is ascertained at regular intervals up to 14 days. The moisture content of the soil is brought up to 60% of its maximum water-holding capacity.

The soils are incubated in 250 ml biometric flasks as shown in Figure 2.⁴⁰ The CO_2 is absorbed by standard alkali (0.1 or 0.1 N NaOH) contained in the tube connected to the reaction flask. Absorption samples can be withdrawn periodically to determine the rate of microbial activity. The alkali from the test tube is titrated in one operation after the carbonate is precipitated with excess neutral barium chloride (20%), usually about 10 ml. For the titration, 0.1 N HCl is used.

Another well-known respirometer assembly may be used as illustrated in Figure 3. Although it is less convenient than that shown in Figure 2, it has been used successfully for many years by microbiologists to determine the total carbon respired and estimate the rate of CO_2 evolved by soil as influenced by organic residue additions. The procedure uses simple easy to make equipment and, therefore, is offered here for prospective users.

The CO_2 evolution from 100 g of soil (on a dry-weight basis) ground to 5 mesh, alone and with the addition of 1 g or any other suitable amount of organic waste, is ascertained at regular time intervals up to the total period desired. The wastes are ground when necessary to pass a 20-mesh sieve which has been heated at 85°C for 24 hours to kill the greater portion of the organisms present. The moisture content of the soil is brought up to 60% of its maximum water-holding capacity plus 3 ml if bulk materials are added. The soils are incubated at 25°C in bottles closed with appropriate stoppers through which pass two glass tubes terminating in rubber tubing closed with sections of glass rod, Figure 3. The CO_2 is absorbed by standard alkali contained in short wide test tubes (approximately 2 × 12 cm) resting on the soil. Prior to titrating, the bottles are briskly aerated for 15 min into Truog towers also containing standard alkali. The combined alkali from the tower and the test tube are titrated in one operation after the carbonate has been precipitated with excess neutral barium chloride.

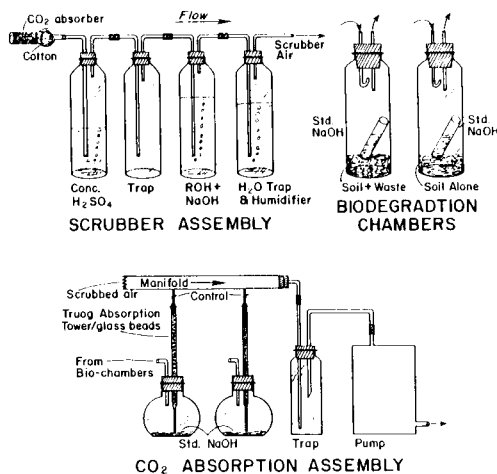


FIGURE 3. Illustration for the assembly of a CO_2 -absorption respirometer. (From Fuller, W. H. and Gairaud, C., *Soil Sci. Soc. Am. Proc.*, 18, 33, 1954. With permission.)

E. Acute Microbial Toxicity and Biodegradation

1. Toxicity Reduction via Microtox™ Analyzer

Laboratory toxicity reduction experiments — The Microtox™ System utilizes a suspension of marine luminescent bacteria as bioassay organisms for measuring acute toxicity in aqueous samples. The suspension of approximately 10^6 bioluminescent organisms is “challenged” by the addition of several concentrations of an unknown sample. The Microtox™ Toxicity Analyzer with attached recorder is used to quantitatively measure and record the light output of the organisms before and after they are challenged. A reduction of light output reflects a deterioration in the state of health of the organisms, thereby signifying presence of toxicants in the sample. The use of such a large population of assay organisms gives Microtox™ results very high resolution and statistical significance. A comprehensive discussion of the Microtox™ System, including its special merits and limitations, principles of operation, operating procedure, and basic data reduction schemes, has been prepared for distribution by Beckman Instruments, Inc.⁴¹

The Laboratory Toxicity Reduction (TR) experiment involves preparation of a duplicate series of Erlenmeyer flasks containing selected waste-soil mixtures which are tested at selected intervals over a 42-day period. Each test series is maintained under constant temperature ($20 \pm 2^\circ\text{C}$) and moisture conditions (15 to 25%). Flasks are arranged in test sets for Microtox™ testing on days 0, 7, 12, 21, 28, 35, and 42. The actual test mixtures and chemical analyses for each test series are based on results of preliminary bioassays and chemical characterization of the selected waste and soil. If the Electrical Conductivity at 50% growth decrement (EC50) for the bioassay of the raw waste is $\leq 0.5\%$, it is assumed that the waste cannot be safely or economically land treated without some form of pretreatment and the experiment is terminated.

After preliminary bioassays of the waste and soil have been conducted, the test mixtures to be used in the toxicity reduction experiment are selected and prepared. Soil to be used in the experiment is air-dried for 72 hr and then broken into small, uniform particles. Thirty grams of soil are added to each flask, adjusted to 25 wt% moisture, and allowed to acclimate for 7 days. Following the acclimation period, appropriate weights of sludge are added to the flasks to give the selected weight percent, waste soil mixtures. Commonly, three waste soil mixtures are used in the experiment. These mixtures reflect the percent dilution causing a 50% light decrease (EC50) in the bioassay of the raw waste, one half the EC50 value, and twice the EC50 value. After waste addition, the waste and soil in each flask are thoroughly mixed to begin day 0 of the experiment. Control flasks with no waste and 100% waste

addition are also prepared for testing on day 0. If desired, control flasks can also be prepared for testing at selected intervals throughout the duration of an experiment.

Day 0 samples are prepared for extraction with distilled water immediately after preparation, using a modification of the mixing methods employed by the California Department of Fish and Game in their Hazardous Waste Evaluation Project. The extraction procedure used in the TR experiments involves adding 500 mL of distilled water to each waste-soil mixture (30 g) and shaking at approximately 150 rpm for 24 hr. After shaking, samples are allowed to settle 1 hr and the decant filtered and refiltered through Whatman® #5 filter paper to provide 20 mL of filtrate. The filtrate is prepared for Microtox™ testing by adjusting to the proper osmotic pressure with 0.4 g sodium chloride. If required, the remaining nonfiltered sample is then stirred and an aliquot taken for TOC analysis using the Beckman Carbon Analyzer. Additional or alternative chemical analyses, e.g., oil content, specific organics, may be conducted if deemed appropriate by results of the preliminary waste characterization tests. The same procedure is followed for all subsequent sample sets.

2. Field Plot Toxicity Reduction Experiments

The field plot TR experiment involves establishment of a series of field plots which are sampled periodically for Microtox™ testing and chemical analyses. These experiments are used to verify results of the laboratory experiment. In addition to verifying degradation at the predicted loading rates, the potential use of Microtox™ results to predict when reapplication of waste can be made is determined. Microtox™ results are compared with results of extensive chemical analyses.

Four field plots are prepared and used for most verification experiments. Wastes are applied to field plots at the three loading rates used in the laboratory TR experiments. Following waste application, the plots are mixed thoroughly by rototilling. A control plot with no waste addition is prepared and maintained under the same conditions.

After mixing, composite samples are collected for day 0 Microtox™ testing and associated chemical analyses. Samples for Microtox™ bioassays are prepared the same as for the laboratory TR experiments. Subsequent composite samples are collected at 28 day intervals and handled in the same manner as for day 0. Following each sample collection date, the plots are rototilled to maintain aerated conditions in the treatment zone. In the initial experiments, reapplication of wastes are made when the EC50 exceeds 100%. The time required to reach this point will be compared to that indicated in the laboratory experiments. The verification experiments are conducted for approximately 6 months (168 days). It is believed that this time period is appropriate to verify laboratory results and to explore the use of Microtox™ bioassays for predicting when reapplication of wastes can be made.

3. Dehydrogenase Activity Method

Dehydrogenase activity is assayed with the selected hazardous wastes serving as electron-donating substrates.⁴² The assay procedure is carried out as described by Casida et al.,⁴³ with the addition of 1 mL of 3% 2,3,5-triphenyltetrazolium chloride (TTC) and 2.5 mL of deionized water. After 24 hr of incubation at 37°C triphenylformazan (TPF) is extracted by filtering through a Whatman #42 filter paper for 4 successive portions of methanol totaling 100 mL. The filtrate is refiltered and the color intensity determined in micrograms by reference to a calibration plot, using a spectrophotometer at 485 nm with methanol as a blank.

Dehydrogenase activity is expressed in micrograms of formazon per gram of soil per 24 hr. For comparison of activity, the literature reports activity values in microliters of H₂ produced for reduction of TTC to TPF where 1 mg of formazon requires 150 µL of H₂.⁴⁴ Also see Frankenberger and Johanson⁴⁵ for additional details concerning an application to crude oil and refined petroleum.

Table 2
COMPILATION OF BIOLOGICAL SYSTEMS FOR MUTAGENIC
MANIFESTATIONS, THE ASSOCIATED GENETIC EVENTS DETECTED, AND
METABOLIC ACTIVATION

Organics	Genetic event detected		Metabolic activation
	Gene mutation	Other types of genetic damage	
Insects			
<i>Drosophila melanogaster</i>	Recessive lethals	Nondisjunction, deletions	Insect
Habrobracon	None developed	Dominant lethals	Insect
Mammalian cells in culture			
Chinese hamster ovaries	Forward, reverse	Chromosome aberrations	Mammalian
V79 Chinese hamster cells	Forward, reverse	Chromosome aberrations	Mammalian
Chinese hamster lung cells	Forward	Chromosome aberrations	Mammalian
Human fibroblasts	Forward	DNA repair	Mammalian
Human lymphoblasts	Forward	DNA repair	Mammalian
L5178Y mouse lymphoma cells	Forward	Chromosome aberrations	Mammalian
P388 mouse lymphoma cells	Forward	Chromosome aberrations	Mammalian
Human peripheral blood lymphocytes	Forward	Chromosome aberrations	Mammalian
Various organisms	None developed	Sister chromatid exchange	Mammalian

Modified from Brown, K. W. and Associates, Inc., Hazardous Waste Land Treatment, EPA-SW-874, U.S. Environmental Protection Agency, 1983, 735.

All of the toxicity methods may report results on a basis of percentage decrease or increase in activity compared with the untreated soil as 100 for the same temperature and moisture conditions.

F. Chronic Microbial Toxicity and Mutagenicity

1. Microbial Mutagenicity

Toxicity of wastes may be determined by a large number of methods, but none of these are useful for identifying the more subtle mutagenic manifestations. In response to a demand for a method to indicate the presence of compounds which cause genetic damage, a large number of microbial, plant, and mammalian cell culture assay procedures have been developed. Some of the biological systems, the associated genetic events detected, and metabolic activation are compiled in Table 2.

The chronic genetic toxicity of various extracts, dilutions, and soil-treated (incubated) wastes can be detected by a number of microbial systems.⁴⁶ Since there are numerous methods and tedious procedures of extraction, each depending on the kind of waste, wastewater, and pretreated wastes, there is no purpose served by providing the voluminous details that necessarily accompany the methods of detection of genetic toxicity. References must be studied directly. Extraction procedures and chronic toxicity testing with solid wastes also appear in a U.S. EPA publication.⁴⁷ Most investigators caution against overinterpretation of results of the mutagenicity responses, at this stage of research, especially with respect to relative hazard or negative findings. The validity of the apparent correlation between mutagenicity and carcinogenicity still remains an issue to be validated through basic research.

G. Phytotoxicity

1. Seed Germination Method

The seed germination test has been adapted for evaluating the tolerance of seeds for salty soils during the germination period. It has equal value for evaluating other toxic conditions

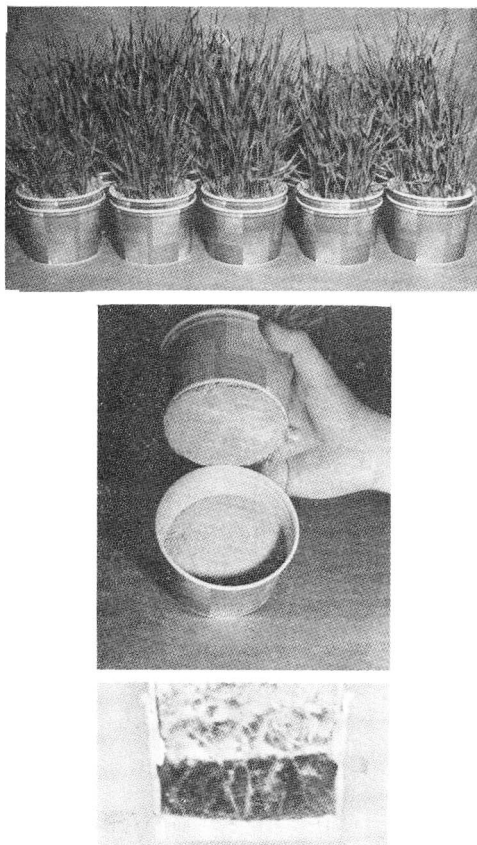


FIGURE 4. Seedling establishment method. (A) Oat plants grown for approximately 17 days in sand; (B) placement of the root mat of plants in contact with the soil; (C) cross-sectional view of sand soil culture after 5 days of root-soil contact, showing penetration of roots into the soil. (From Stanford, G. and Dement, J. D., *Soil Sci. Soc. Am. Proc.*, 21, 612, 1957. With permission.)

in soils such as may be present with wastes containing solid waste, phenols, xylene, acids and alkalis, organic solvents, etc.

The methodology is simple, efficient, and rapid. The test can be done in petri dishes or small growth chambers consisting mostly of oversized petri dishes (30 cm diam.). Either the treated soil or extract of the soil is placed in the petri dishes at a depth of 5 to 10 mm and a standard number of seeds of desired food plants placed on the land-treated soil and moistened. A wet filter paper can be placed over the seeds and the system allowed to set until germination is declared complete in a standard time period of 7 to 10 days. Percentage germination is then determined. Some innovations or modifications may be required to satisfy the suitability of the procedure as described for better adaptation to the objectives of waste-treated soils.

2. Seedling Establishment Method

The procedure described as the Stanford-DeMent test can be modified to evaluate the fate, transport, and degree of biodegradation of the waste-treated soils.^{48,49} A test equipment (pots, plants, roots, and containers) is shown in Figure 4. The technique allowed for

measurement of (1) health and vigor of the oat or barley seedlings, (2) the absorption of pollutants into roots and tops, and tissue damage to root-mat.

The test is simple, rapid, and convincing. It consists of growing 100 oat or barley seedlings for approximately 17 days in quartz sand in cottage cheese containers. Placing the root mat developed (Figure 4) by the seedlings into contact with another container (after removing the bottom of the seedling container) of the hazardous waste land treatment soils to be tested and allowing to grow for a few days. There are several acceptable modifications of this procedure.⁴⁹

3. Root Mat Technique

The root-mat technique is similar to the Short-term Plant Seedling test. The root-mat and assembly used to measure pollutant transfer from soil to root and evaluate health and vigor of new roots and shoots also is similar. Here, too, modification is necessary in small measure to adapt the test to HWLT soils. See Dean and Gledhill for details of the root-mat technique.⁵⁰ Seedlings of oats or barley are grown in small containers (6.5 cm diam.) on a screen over nutrient solution. The root-mat is then removed and placed in a container of the same size on the soil to be tested. The root-mat is removed, washed, and analyzed for pollutant or dried and weighed for growth reaction.

H. Mineral Excess and Plant Growth Decrement

Sometimes short-term tests do not provide the desired information on acute or residual waste phytotoxicity. Moreover, owing to the high degree of variability in the composition of "normal" plants under a variety of different conditions of growth, the growth response as well as the chemical composition of the plant parts should be accepted as only one line of evidence in the diagnosis of phytotoxicity. Corroborative evidence may be required. For example, sugar beets which are very salt-tolerant during mature stages of growth are very sensitive during germination.¹⁵ Barley is most tolerant to salts at all stages, but yet is slightly more sensitive during germination than later stages. Salt tolerance of test plants can be an extremely important factor in test procedures since many wastes contain relatively high concentrations of soluble common salts as compared with that of soil solution. The controlled environment pot and field-plot techniques, therefore, can provide for some necessary corroborative evidence to strengthen findings of other tests, but it is more important to sort out and identify more realistically the nature of the phytotoxicity, if it really is phytotoxicity.⁵¹

1. Controlled-Environment Pot Experiments

Controlled environment pot experiments, to evaluate the nutritional status and salt tolerances of economic crop plants, have been on going at every agricultural experiment station in the U.S. for many decades. So many innovations have occurred that it is often not possible to trace the origin. Therefore, the techniques are well known and quite flexible. The physical method for waste evaluation is little different from fertilizer testing. Soil and waste material or liquid waste are mixed at different rates of known application placed into pots which are seeded to an indicator crop or plant of known behavior. A parallel set of pots containing no waste are established as comparative controls. Usually 30 to 45 days are sufficient to determine the level of phytotoxicity. Growth responses of plants in soil with and without waste are compared. A reduction of 50 and 75% of the control yield is sufficient to establish "critical concentration" for the level of waste applied.

Whereas the toxicity reduction method evaluates the acute toxicity of the water-extractable components of the waste with respect to the bacterial system, the controlled environment pot method evaluates the acute toxicity potential to a vascular plant species. One variation of these pot experiments suitable for assessing the residual toxicity of hazardous wastes to provide information as to optimum loading rates as suggested by Brown and Associates, Inc. is as follows.²⁴

Plastic pots, 15 cm I.D. \times 15 cm deep, are filled with 2000 cm³ of test soil on an air-dry basis having been charged at three selected levels of the test waste and 1 g of N-P-K fertilizer, usually a 17 \times 17 \times 17 mix. The surface is seeded to rye grass (*Lolium multiflorum*) (some other suitable plant such as barley may be used depending on the nature of the waste to be tested). The pot treatments are set up in replicates of three for each level of waste loading. Usually, three different loading rates are tested. The test pots, including untreated soil controls are maintained in controlled environment for the full experimental period with a 12-hour light/12-hour dark pot period. Moisture is maintained also by routinely weighing the pots and adding deionized water. The step-wise procedure is as given in detail:

1. Four "loading" levels of soil-waste mixes are prepared and pots are filled with 2000 cm³ of the mix. Six pots each are prepared for the loading levels of 0, 1, 2, 3, as predetermined.
2. Incorporate 1 g of N-P-K (17-17-17) fertilizer to each pot and adjust the moisture to 65 to 70% water-holding capacity with deionized water.
3. After a 24-hour adjustment period uniformly distribute 100 ryegrass seeds on the surface of one set of test units (each replicated 3 times) and leave another set unplanted.
4. Record the seed emergence beginning on day 4.
5. Continue to adjust pot moisture daily if necessary.
6. Clip ryegrass at the soil surface in about 35 days after seeding. Record the dry matter production after drying at 60°C.
7. Cultivate the second set of test soil-waste pots on day 35, adjust moisture again to 65 to 70% WHC, and allow to stand 24 hours before seeding as described before.
8. Repeat the experiment as before and conduct the desired chemical analyses on the vegetation tops of all sets.
9. Calculate emergence of grass seedlings. The waste concentration (loading) is considered to be phytotoxic when the yield is reduced more than 25% from the control yield.

The use of the three methods, namely, soil respirometer (CO₂-evolution), Microtox[®] (toxicity reduction, TR), and controlled-environment pot (vascular plant) should be sufficient to evaluate the acute toxicity of a waste.

Additional information may be obtained about acute toxicity by comparing the mineral composition of plants grown on treated and untreated soils. These data then can be applied to some method of determining loading rates. Loading rates, however, must take into consideration all three values for limiting constituents (LC) in the waste, e.g., concentration (CLC), rate (RLC), and application (ALC).

Residual phytotoxicity is concerned with certain resistant organics that offer no particular plant growth problems at low concentrations until multiple applications have been made. If the growth-limiting factor is some identifiable constituent in the waste, enriching the waste with that constituent or pure compound will provide a means of establishing critical levels and for loading by repeating the pot experiment just described.

Also, respirometer waste degradation data can be helpful in conjunction with the greenhouse experiments to evaluate toxicity of wastes and ultimate treatability.

2. Field-Plot Experiment

Field-plot experiments brings us one step nearer to the actual site facility operations. Again, the agricultural experiment station and USDA personnel throughout the U.S. are the experts in field-plot experimentation. Because of the great variability in field results, statistical methods have been applied to interpret significances due to treatment, environmental-related factors, etc., free from human bias. Detailed description of field-plot tests would serve no real purpose here since each site, each soil, and each environment requires its own design. Field-plot studies may be used as a diagnostic tool in waste disposal to:

1. Verify laboratory and controlled-environment plot results
2. Identify field-oriented problems not detectable in the laboratory
3. Integrate site conditions into a single system
4. Evaluate the erosion factors
5. Evaluate odor and volatilization problems
6. Evaluate more closely the soil-waste reactions at unusually high rates of application not realistic with other test methods

Field-plot techniques have been described in fine detail in a publication by LeClerc et al.⁵²

I. Permeability

The present (1983) U.S. EPA Interim *Final Rule on Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facility*⁵³ rules for landfill and disposal surface impoundments, with the goal of eliminating the escape of leachate from land-based waste management facilities (to the extent of practicable), eliminates the use of clay liners because some migration into the liner will always occur. The emphasis, therefore, for certain disposals is on permeability and hydraulic conductivity rather than on pollutant attenuation, sorption and mobility. Organic solvents are particularly susceptible to this rule partly because they tend to flow more rapidly through soil than water and partly because of their wide range of toxicity to humans.

Methods for determining hydraulic conductivity (permeability) are discussed in Chapter 1, Volume I. According to Ely et al.⁵⁴ in a recent review on the performance of clay caps and liners, there are no standardized procedures for determining permeability in the laboratory or in the field. Two methods used in engineering, the (1) triaxial or (2) fixed-wall permeameters, provide acceptable results with water for quality control testing of clays. Other test devices also may provide usable results when care is taken to eliminate the source of error as much as possible. The triaxial cell probably is inappropriate for measuring chemical permanent fluids because of shrinking and swelling effects. The double-ring compaction permeameter can provide acceptable permeability values.

Permeability tests are sensitive to many conditions of the procedure as well as the nature of the liquid. In fact, Ely et al.⁵⁴ conclude that it is probably unrealistic to expect permeability test results to agree within less than several fold. Some of the variables that are required for further standardizing are

1. Duration of the tests — the permeability test should be ended only when the values become constant or stable in flow rate.
2. The moisture content at the time of compaction must be standardized, probably to that in the field from which the soil sample comes would be most desirable.
3. Consolidation theory is not recommended for use in computing permeability values.
4. Permeability for compatibility testing and quality control measurements appear to be best suited to the laboratory because of the great variability in field testing and excessive time required to arrive at acceptable data.

J. Volatilization

Volatilization is an important property of waste disposal for several reasons:

1. Dissipation of wastes into the atmosphere which represent actual waste reduction
2. Dissipation sufficiently extensive to represent an air pollution hazard needing attention
3. Residue remaining after volatilization will be different from that of the original waste
4. Calculations of waste reduction must have some input data on volatilization losses to establish meaningful balance sheet information.

Volatilization has been considered a significant factor in disposal for those compounds with vapor pressure greater than 10^{-3} mmHg at room temperature, according to Weber.⁵⁵ Volatilization may be measured by a number of methods. The most meaningful originate in the field from soil surfaces. One of the most effective devices has been developed to determine losses directly from the soil surface by placing a chamber of known dimensions and volume over the soil surface, passing an inert gas such as argon or nitrogen into the chamber, and collecting the volatiles and gases swept into absorption tubes placed in line for analysis (OV A Snifter, Fox Buros®). The soil and air temperature, humidity, wind movement, and other necessary parameters, depending on location, are recorded at the time of sampling.

Empirical determinations may be made by measuring vapor losses from a known soil surface following the placement of the waste material and final disposition. Laboratory methods involving evaporative transfer from a free liquid surface depend on the use of a sealed, flow-through system. Serious volatilization hazard may be reduced mainly by limiting the rates of application and by soil incorporation using air quality standards for establishing the best management programs.

K. Soil Erosion

1. Soil Loss Equation

The universal soil loss equation is used for predicting soil losses on nonirrigated cropland, range land, woodland, construction sites, and critical areas. It is used to estimate sheet and rill erosion as the water accumulates into runoff. The universal soil loss equation does not estimate stream channel and gully erosion and sediment yield. The equation is

$$A = 2.24 RKLSCP \text{ (metric units)} \quad (1)$$

where

- A = the estimated annual soil loss in weight per unit area
- R = the rainfall factor or rainfall erosion index
- K = the soil-erodibility factor
- LS = the length and steepness of slope factor
- C = the cropping-management factor or native plant cover factor when the formula is used on noncropland
- P = the erosion control factor for such practices as terracing, strip cropping, or contouring.

The equation and its implications are discussed in Volume I, Chapter 4.

2. Wind Erosion Equations

The mean wind velocity-profile equation over stable surfaces is ⁵⁶

$$u_z = (u^*/k) \ln[(z - d)/z_0] \quad (2)$$

where

- u_z = wind velocity at z height (L/T)
- u^* = friction velocity (L/T) = $(\tau_o/\rho)^{1/2}$
- τ_o = shear stress at the boundary (M/T²/L)
- ρ = air density (M/L³)
- k = von Karman's constant usually taken as 0.4

- z = height above a reference surface (L)
 d = an effective surface roughness height (L)
 z_0 = a roughness parameter (L)

In addition to the mean wind velocity-profile equation above, a wind erosion equation has been developed to indicate the relationship between the amount of wind erosion and various field and climatic factors that affect erosion.^{57,58} The equation serves two purposes, namely: (1) to calculate the amount of wind erosion taking place on any field under the specific climatic conditions of the selected disposal site and (2) to use as a guide for calculating the conditions of surface roughness, such as cloddiness, gravel or soil, vegetative cover, sheltering, or dimensions of the site necessary to reduce the potential wind erosion to an acceptable amount.

The wind erosion equation is

$$E = f(I, C, K, L, V) \quad (3)$$

where

- E = weight of annual erosion per unit area
 I = a soil erodibility index
 C = a climatic factor
 K = a soil ridge roughness factor
 L = equivalent field length along the prevailing wind erosion direction
 V = equivalent quantity of vegetative cover

The wind erosion equation cannot be used as a simple mathematical expression because of the complexity of factors defining the equation. Moreover, each local site will possess peculiarities that must be identified and quantified as part of the equation.⁵⁸ Further discussion is in Volume I, Chapter 4.

3. Water Runoff

The water runoff conditions of waste disposal and treatment sites must be controlled at all times. Detailed soil management practices for runoff control are recommended by the USDA Soil Conservation Service.⁵⁹ An earlier discussion in Volume I, Chapter 4 should be reviewed for runoff methods adopted for specific site conditions. The USDA Soil Conservation Service method of runoff evaluation resulted in the following equation which can be used for calculating runoff volume in small watersheds:

$$Q = \frac{(I - 0.2S)^2}{I + 0.8S}$$

where

- Q = direct surface runoff depth in mm
 I = storm rainfall in mm
 S = maximum potential difference between rainfall and runoff in mm, starting at the time the storm begins

Rain gauges placed in appropriate locations at proposed disposal sites and facilities can be very useful and are recommended. For example, on gauged watersheds, I can be plotted against Q and the value of S obtained directly. Runoff decreases as S or infiltration increases. Under those circumstances where runoff cannot be prevented, collection and treatment of runoff water eliminates any excessive control which runoff hazards may exert on disposal designs.

L. Attenuation

Predicting movement of hazardous waste constituents in soils may be approached in several quite different ways. Indeed, new experiments are continually being suggested in an attempt to improve predictive capabilities.^{5,6,46,60,61} The most used methods may be grouped as follows:⁶

- Field studies involving test drilling and sampling
- Field studies involving suction lysimetry
- Field studies involving resistance measurements
- Simulated aquifer method
- Batch soil-contact technique
- Column soil-contact technique

Each method harbors limitations in meeting the criteria for a universal predictive tool. In the present search for a more quantitative predictive approach, certain criteria are anticipated which must feature a technique that is

1. Rapid
2. Uncomplicated
3. Reproducible
4. Reliable
5. Readily available to most waste managers as a field-oriented tool

Despite its limitations, the column soil-contact (soil-column) technique appears to be the most promising to generate the kind of data necessary for model-predictive purposes. We will discuss Soil-Column Techniques in Chapter 5 soon to follow. In the meantime, we first look at batch studies, thin-layer chromatography, and lysimetry.

1. Batch Studies

The batch study, or better known among chemists as batch test, is a system wherein a known volume of solid particles, such as resin or soil is contacted with a known volume of solution and the change in concentration of the solution phase is measured either as a function of time or after a set contact period. Usually batch studies are conducted with small amounts of soil suspended in fairly large volumes of solution (aqueous). Soil-to-solution (leachate) ratios usually range from 1:5 to 1:20. Contact is assured by shaking or rotating the reaction containers varying from a few minutes of vigorous shaking to 24 hours. Soil cation exchange reactions, however, usually are shaken for only 2 hours. Batch studies are most useful when:

1. A large number of soils need to be screened for removal of a specific solution component.
2. Large organic molecules of little known reactions, such as complexation with heavy metals, are involved.
3. A number of possible regenerants and regenerant concentrations must be evaluated.
4. The effect of temperature on either the loading or elution cycle must be known.
5. The available amount or volume of the test solution is small or limited.

6. There is need to narrow down variables and select the most promising soil or soil-to-solution concentrations.

The batch test finds a “best” application among chemists for evaluating resin chemistry, solution concentrations, volume relationships, and resin selections. Direct application of batch test data to field site design is often not a realistic practice, particularly as it relates to attenuation of pollutants by soils, partly because the soil in a column (profile) does not make contact at all depths with the same influent but an altered fluid that changes as it progresses down the column.

2. Soil Thin-Layer Chromatography

The attenuation principles of the soil batch study and the soil thin-layer chromatography share a number of the same reactions and limitations. Both procedures relate mostly to relative solubility of organic fraction components and other potential pollutants. Soil thin-layer chromatography is a variation of the conventional thin-layer chromatology. The difference is in the composition of the stationary phase; soil is used in place of such better-known materials as alumina, silica gel, resins, and cellulose. Attenuation of a specific pollutant is reported by a relative measure (R_f). Techniques are described by Helling and Turner⁶³ and Helling⁶² to name a few.

Some disadvantages of the soil thin-layer chromatography are identified as²⁴

1. Contact between waste and soil is maximized, such that it most closely simulates intra-aggregate flow and negates the attenuating effects of soil aggregation.
2. Soil particles orient in two dimensions only.
3. The flow is rapid, minimizing the adsorption-desorption kinetic effects.

3. Lysimeters

Field lysimeters have been used by agricultural experiment station researchers to fulfill a great number of objectives relating to soil water movement, salt and plant nutrient transport in soil, biodegradation assessments, and element transformations. Their position in waste disposal is rather limited, partly because the small field plot technique is often preferred and partly because of cost disadvantages over other simpler field methods. Yet, one can identify advantages where highly toxic substances require more realistic testing than is possible in the laboratory, and strict confinement of leachates, solvents, and solutions are required which often is unsuited for “open” field exploration. The trench lysimeter is a recent innovation for collecting data *in situ*. The advantage of this type is in its economy and ease of manipulation.⁶⁴ Leachate collecting units, installed into the walls of the trench at different levels, function to intercept downward moving water. Sampling, therefore, can be tedious and often slow depending on rainfall or irrigation management.⁶⁵

IV. THE SOIL-COLUMN TECHNIQUE

A. Approach

The soil-column technique has the advantage of screening a large number of soils of wide variability for pollutant attenuation while avoiding the multitude of problems associated with field conditions. The data can be used in two ways, (1) directly for prediction purposes and (2) indirectly through the development of rate equations. The soil-column method is adapted to generating a large volume of data at a relatively low cost. The indirect approach, therefore, is to use soil-column techniques in association with prediction equations as finally applied to the concept of certain universal simulation models. For example, the “Lapidus and Amundson” and “Error Function” models have been adapted to develop user-oriented

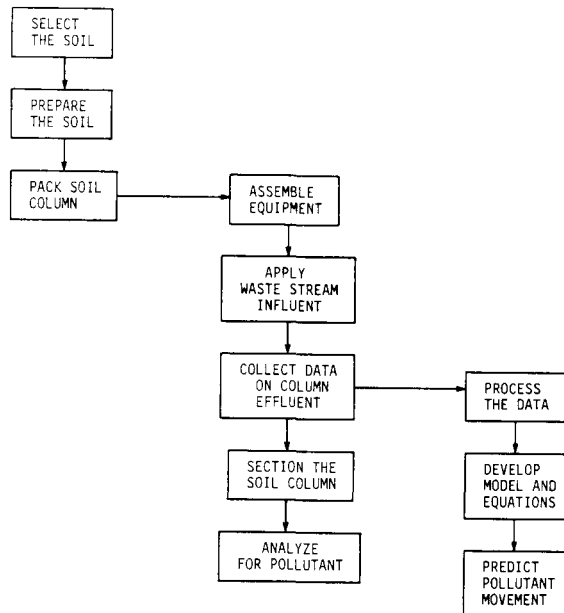


FIGURE 5. Schematic flow-sheet of the soil-column method.

predictive equations of pollutant attenuation provided that certain dominant characteristics of the components of the waste disposal environment have been determined.^{19,66,67}

Predictive designs for land disposal of hazardous wastes must be established on characteristics of the components of the specific disposal environment affecting pollutant migration rates. These characteristics must be sorted out, identified, and quantified.^{5,68} No two pollutants respond identically to the same set of soil or transport system properties. For convenience, the soil-column method is divided into steps as schematically diagrammed in Figure 5.

1. Techniques associated with the soil — sampling, screening, moistening, packing the column
2. Techniques associated with the column influent (aqueous solutions or solvents) — collecting anaerobic leachates, maintaining stability of solutions while under operation, operating equipment for different fluids
3. Techniques associated with the column effluent — collecting samples, preserving samples, analyzing for pollutant
4. Data processing — breakthrough curves, plotting attenuation, pollutant movement, incorporation of variables
5. Predicting pollutant movement — direct application of breakthrough curves and development of models and universal prediction equations

B. Techniques Associated with the Soil

1. Soil Selection

Enough soil should be collected for two purposes: (1) for immediate soil-column tests and (2) for future reference. The single most important requirement of collecting a soil sample for testing is that the sample be representative of the soil located in the proposed disposal site. The more heterogeneous the site, the greater the number of soil samples required to represent the area.

To insure reproducibility of results and valid comparisons among different leachates and fluids for pollutant attenuation, a set of reference soils should be established in sufficient

quantity to last over several years of intensive testing. These standards then can be reserved for all other tests and thereby act as references for comparative purposes for new or expanded disposal site selections. Table 3 is an example of background data for such reference soils representing seven of the ten soil orders. Selection of soils for the column tests and laboratory characterization depend on a great number of site characteristics. Some most closely related to soil have been identified in Chapter 7.

2. Preparing the Soil for the Column

Soils are collected for the test in sealed plastic bags and air-dried sufficiently to permit them to be rolled with a wooden rolling pin and passed through a 2 mm sieve. They should be packed immediately to prevent excessive drying. Experience has demonstrated that moisture loss, to about the wilting percentage for plants (15 bars), does not affect, appreciably, soil behavior toward attenuation of pollutants. Excessive air drying, however, may influence attenuation as one may expect attenuation to take place with the soil under natural field conditions.⁶⁹ Should the selected field samples become excessively dry, they may be re-moistened and placed in plastic bags for 20 to 30 days to regenerate the soil microflora. Another technique is to wet the soil in the soil column and allow it to drain and the moisture content to equalize for about 10 to 20 days before applying the selected waste liquids for testing.

If the soil contains rock, stones, and gravel larger than 2 mm, the percentage volume loss should be accounted for when evaluating the potential attenuation of the soil.

3. Packing the Soil in the Column

Uniformity of packing the soil into columns is critical for attenuation tests where the procedure calls for using disturbed soil.

The first step with disturbed soil is to determine the natural bulk density before collection. Lumps or clods of the soil are taken for this purpose and the bulk density is determined as described in the section on physical analyses. The object is to try to bring the soil up to or slightly above the natural bulk density to insure sufficient uniformity among different columns to obtain reproducibly acceptable attenuation data. Since the procedure is empirical, each step requires the investigator himself to establish uniformity and standardization. For example, funneling loose soil into the soil columns will result in particle segregation and stratification of material. To avoid this as much as possible, a certain amount of soil (1 to 2 cm) is spooned into the column and packed uniformly with a rounded thick glass rod or steel rod covered with durable plastic. This process is repeated until the column is filled to the predetermined mark (10, 20, and 30 cm).

Excessive channeling and piping through the soil column is to be avoided. Proper packing is the only means of minimizing these problems. Should unacceptable channeling and piping be identified, the soil column must be repacked or replaced.

Some soils form unusually stable structures (i.e., particle arrangement) when removed from the natural habitat and dried. They subdivide poorly, if at all, during packing and slake poorly during rewetting. Soils relatively high in the hydrous oxides of Fe and Al, and to a certain extent Mn, typically form cemented durable structures during the drying process associated with preparation in the laboratory. Soils containing hydrous silicates and free calcium carbonate (lime) and calcium sulfate (gypsum) may also exhibit particle cementations that are quite stable to water. The structures form large, open-pore spaces like coarse sands, rather than the smaller-pore spaces of fine-grained soil. Compare attenuation in soils of different textures as shown in Figure 6. Unless tightly packed, the real attenuation in such soil is difficult to evaluate and aqueous leachates and solvents pass through the column so rapidly that penetration and diffusion into the structures is unnaturally slow as compared to that in the field with undisturbed moist soil. Contact with internal particle surfaces is so

Table 3
CHARACTERISTICS OF THE REFERENCE SOILS

Soil series ^a	Soil order	Clay (%)	Silt (%)	Free iron oxides (%)	Soil paste pH	Cation exchange capacity (meq/100 g)	Elec. cond. of extract (μmhos/cm)	Column bulk density (g/cm ³)	Column porosity	Particle density	Soil surface area (m ² /g)	Predominant clay minerals ^b
Davidson	Ultisol	52	23	17.0	6.4	9	169	1.40	0.476	2.63	151.3	KK
Molokai	Oxisol	52	25	23.0	6.2	14	1262	1.44	0.429	—	167.3	KK, G
Nicholson	Alfisol	49	47	5.6	6.7	37	176	1.56	0.460	2.57	120.5	V
Fanno	Alfisol	45	19	3.7	7.0	33	392	1.42	0.484	2.79	122.1	MT, MI
Mohave (Ca)	Aridisol	40	28	2.5	7.8	12	510	1.54	0.446	—	127.5	MI, MT
Chalmers	Mollisol	31	52	3.1	6.6	22	288	1.44	0.453	2.60	95.6	MT, V
Ava	Alfisol	31	60	4.0	4.5	19	157	1.44	0.478	2.71	61.5	V, KK
Canelo	Alfisol	26	29	4.2	5.4	6	185	1.55	0.480	2.62	35.0	KK
Anthony	Entisol	15	14	1.8	7.8	10	328	1.85	0.360	2.71	49.8	MT, MI
Mohave	Aridisol	11	37	1.7	7.3	10	615	1.75	0.365	2.79	38.3	MI, KK
Kalkaska	Spodosol	5	4	1.8	4.7	6	237	1.59	0.404	2.59	8.9	CL, KK
Wagram	Ultisol	4	8	0.6	4.2	2	225	1.84	0.378	2.82	8.0	KK, CL
River alluvium	Entisol	1	2	0.3	7.2	2	210	1.78	0.336	2.62	3.6	KK, MI

^a Oriented on basis of clay content.

^b Listed in order of importance: KK, kaolinite; G, gibbsite; MI, mica; MT, montmorillonite; V, vermiculite; CL, chlorite.

From Fuller, W. H., Movement of Selected Metals, Asbestos, and Cyanide in Soil: Application to Waste Disposal, U.S. EPA-600/2-77-020, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977, 28.

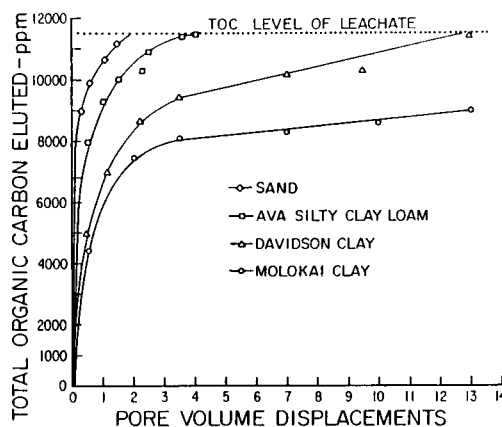


FIGURE 6. Relative movement of organic carbon constituents of 1½-year-old MSW leachate through 4 soils of different clay content.

incomplete that attenuating physical and chemical reactions buried within the internal structures may have little or no opportunity to take place fully during the test. Excessive air drying, therefore, is to be avoided. To determine soil moisture levels, a separate 100 to 200 g sample of soil may be oven dried as a means for calculating data on a dry weight basis.

In addition to monitoring bulk density, air permeability may be used to evaluate uniformity. This is done by measuring air permeability after packing and discarding columns not falling within a given range, e.g., 10% of a mean value.

C. The Transport Vehicle — Four Major Categories

The soil-column method is flexible. The specific technique employed will depend largely on the nature of the transport vehicle which will dictate the type of disposal on land, whether land treatment/utilization, burials, landfills, lagoons, surface impoundments, or flood or sprinkling irrigation. The nature of the transport system or solvent vehicle carrying the waste requires that certain parameters be incorporated in the soil-column procedure if it is to be representative of the real environment. The characteristics of the different wastes, however, are so divergent or interdependent that, for the most part, the nature of the transport system or solvent forms the dominant practical basis for testing. The soil-column techniques to be described fall into four major categories based on the solvent involved, namely,

1. Dilute aqueous inorganic and aqueous inorganic/organic — Category A is represented by dilute aqueous waste streams of industrial origin containing heavy and/or toxic metals (usually dilute acidic or dilute basic aqueous solutions), MSW leachates containing both heavy and toxic metals in dilute acidic or basic solutions with soluble organic constituents, or acid rains.
2. Aqueous organic — Category B is represented by aqueous solutions containing soluble organics, many of which are solvents dissolved in water from either the disposal waste stream or soil solution or both.
3. Strong aqueous acids, bases, and oxidizing agents — Category C is represented by strong concentration of acids, bases, and oxidizing agents.
4. Organic (solvents) — Category D is represented by a transport system which is wholly and completely organic and is best represented by organic solvents.

A brief description of each category is provided to better explain the reasoning behind the separations as related to the most suitable soil-column equipment to employ.

1. Dilute Aqueous Inorganic and Aqueous Inorganic/Organic Fluids — Category A

Water is involved in almost all leachate reactions in soil. It is the transport vehicle for strong acids and bases and becomes the solvent in secondary leachate even though it may not be present as the solvent in the primary fluid. Soil columns are brought to a saturation equilibrium with water and/or the testing fluid prior to beginning the attenuation evaluations. Thus, the soil-column procedure attempts to provide some degree of realistic standardization with respect to soil moisture.

Some characteristics that make water of special interest as a vehicle of transport in disposal fluids are

1. Viscosity (about one centipoise at 20°C) that is temperature sensitive
2. Surface tension (71.9 dyne cm⁻¹ at 25°C) that controls capillary action, retention, and flow properties
3. Strong dipolar moment (1.87×10^{-18} esu) that greatly promotes orientation of water molecules, thus contributing to its quality as a good solvent
4. Dielectric constant (about 80) that also is responsible for the tendency of water molecules to orient to an electric field which is the basis for adsorption of water to soil particle surfaces
5. Sensitivity to solutes — water is highly sensitive to solutes (salts, organic compounds, etc.) that influence a host of physical properties of soil such as shrinking and swelling, piping, heaving, and the hydraulic gradient, and permeability that permit movement of liquid fluids

A good example of mild aqueous waste streams is MSW landfill-type leachates and paper pulp mill effluents. Such fluids generally contain relatively low levels of most inorganic salts, heavy metals, and organics of higher atomic weights than the highly acidic and basic industrial waste streams. To generalize with respect to organic carbon constituents is somewhat unrealistic since industrial waste streams are highly variable in organic solvents, ranging from near 0 to almost 100%. MSW leachates, however, usually are abundantly supplied with both soluble and insoluble organic carbon constituents.^{18,70-72} The organic carbon constituents of young MSW leachates are attenuated or retained rather poorly mostly because they are so abundant (Table 4). Strict MSW leachates biodegrade rather rapidly, however, and are accompanied by an initial rapid decrease in soluble organic carbon (TOC) substances. A decrease in TOC is associated with a tendency for greater retention of the heavy metals by soils as illustrated in Figure 7. Cadmium was held in constant concentration, while TOC was diluted with water. The greater the aqueous dilution, the greater was the attenuation of Cd.

The aqueous fluids of Category A are expected to react less drastically with the natural soil constituents, permit attenuation of pollutants more effectively without soil failure, and permit biodegradation to occur with limited inhibition to a greater extent than fluids of Category C (the strong aqueous acids, etc.). Generally both inorganic and organic pollutants are inseparably comingled during the generation of the waste stream, but the heavy metal content is, more often than not, lower than that of highly acidic industrial waste streams.

2. Aqueous Organic Fluids — Category B

These are strictly aqueous organic fluids not dominated by organic solvents as a transport vehicle. The aqueous waste streams primarily originate from organic chemical industries and contain low to moderate levels of organics (alcohols, ketones, aldehydes, and aromatic and aliphatic complex molecules) dissolved in water. Some are volatile at low temperatures. Pesticides in aqueous solutions also may be represented here. This category was separated from others, primarily on the basis of relatively low levels of heavy and toxic metals and

Table 4
ATTENUATION BY SOILS OF ORGANIC CARBON CONSTITUENTS FROM
MSW LANDFILL-TYPE LEACHATE 6 MONTHS OLD

Soil	Weight of soil (g)	Leachate passed through soil column			Amount of carbon			
		PV	Volume (mℓ)	Depth (cm) ^a	Passed into the soil column (mg)	Retained by the soil (mg)	Per unit soil (μg/g)	Per unit weight of soil per volume leachate (μg/g/cm)
Davidson	291	6.3	610	29.8	4006	720	2473	82.9
Chalmers	300	6.0	554	27.1	3761	768	2562	94.5
Ava	300	5.0	487	23.8	3161	471	1568	65.8
Anthony	330	6.8	546	26.7	3788	315	956	35.7
Kalkaska	385	6.2	509	24.3	3670	164	425	17.5
Wagram	383	5.4	390	19.8	2535	105	274	13.8
Alluvial sand	370	3.5	233	11.4	1415	80	216	18.7

^a Cross-sectional area of the column was calculated by taking the I.D. = 5.1 cm. Depth is reported the same as rain.

From Fuller, W. H., Investigation of Landfill Leachate Pollutant Attenuation by Soils, EPA-600/21-78-158, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1978, 192.

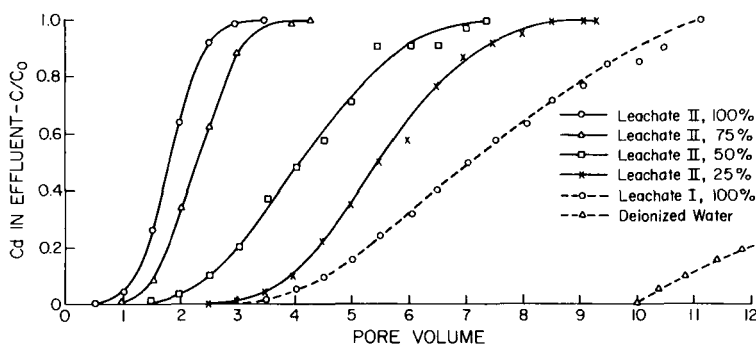


FIGURE 7. Cadmium movement through Ava soil as related to aqueous dilution of municipal solid waste landfill leachates and alone in deionized water. (From Fuller, W. H. and Alesii, A. B., *Environ. Sci. Health*, A14, 589, 1979. With permission.)

greater practicality for identifying the specific polluting organic compound(s) such as phenol(s) and pesticides. Category B also is separated from D on the basis of water solubility and the dominance of water as a transport vehicle.

3. Strong Aqueous Acids, Bases, and Oxidizing Agents — Category C

This category represents waste streams of strong acids and bases originating from industrial processes such as plating, acid baths, and metal-brightening solutions. These fluids are highly corrosive when placed into the soil directly. Soil failure is rapid and complete until neutralized. Past practice has included disposal of these waste streams in shallow, exposed soil surface ponds or in metropolitan sewage facilities.⁷³

Strong acids cause the soil to degrade to the extent that mineral matter breaks down with solubilization of constituents from primary minerals as well as from secondary clay minerals. Podsol-like reactions occur in the presence of strong acids just as in natural soils; Spodosols

form over many years of acidic soil conditions. Iron, aluminum, alkali earths, and a host of other metals may become soluble and migrate leaving a quartz rich residue. Carbonates and carbonate-containing minerals dissolve into the soil solution (Chapter 6).

Strongly acidic waste streams must be tested differently than the less acidic dilute aqueous effluents, leachates, and waste fluids, partly because of the nature of the accelerated reaction between soil and acid and partly because of the usual conditions of disposal of acidic wastes. The reacting soil tends to develop new properties and is more extensively altered by strong acids than by the weaker aqueous fluids. The action of acid also alters the biological properties of the soil. For example, biodegradation may be wholly eliminated in the presence of strong acids and the concentration of dissolved solutes is much higher with a greater contribution from the natural soil itself than for dilute aqueous solutions.⁷⁴ Strong acids, such as concentrated phosphoric acid, also have been observed to seal soils completely against liquid flow causing variable anaerobic conditions in the subsoil below the seal. Failure of the soil to attenuate pollutants occurs sooner by several magnitudes in the presence of highly acidic or alkaline conditions (Chapter 6).

When waste fluids are highly alkaline or caustic, silicate and the silica portion of the soil clay minerals are more readily solubilized than when the waste stream is strongly acid. A good example of alkaline reactions in soils is that found in sodic (black alkali) soils of arid and semiarid lands. Organic matter is readily solubilized, soils disperse, infiltration and permeability become greatly retarded, and anoxic conditions develop with concurrent solubilization characteristic of low redox.⁷⁵⁻⁷⁷

4. Organic Solvents — Category D

Fluids that are wholly, or almost wholly, organic dominate this class of waste. For convenience of the soil-column test, the solvents characteristic of this class may be further subdivided and broadly classified as polar (water soluble) and nonpolar (water insoluble).

The disposal solvents can contain solutes (e.g., metal and/or organic salts) and thereby act as transport systems for a host of hazardous constituents. This is particularly apparent for polar fluids. Preliminary studies with kerosene, xylene, ethylene glycol, and isopropyl alcohol indicate that soil permeability is significantly altered as compared with water by their placement into soil columns.⁷⁸ Changes in soil permeability due to organic solvent alterations in soil have received considerable attention during the early 1980s.^{23,66,67,79,80} A good reason for differentiating this category is the characteristically volatile nature of the many industrial organic solvents. Special equipment must be used to avoid health hazards from fumes. Also, special glassware and pumping and collection equipment must be employed to avoid distortion or solubilization of the conventional plastic tubing, containers, and cemented joints.

D. Equipment Used for the Actual Tests

1. Kinds of Soil Columns

The four kinds of soil columns diagrammed in Figure 8 are used to accommodate a variety of waste stream fluids. Column type A is cut from either 5 or 10 cm I.D. PVC[®] pipe in lengths of 12, 22, or 32 cm. This allows for placement of 1 cm of quartz sand on the surface and on the bottom of the column leaving either 10, 20, or 30 cm of soil depth. The minimum length of the test soil column is 10 cm. Longer soil columns may be used when a larger volume of effluent is needed for chemical analysis or when flux or solution movement through the soil is very rapid. Type A columns are used effectively for MSW leachates and fluids of Categories A and B.

A PVC disc is cut slightly larger than the cylinders with a threaded hole in the center which is fitted with a gas port at the top and a control valve. Fluids and/or water enter the bottom and is pumped against gravity to the top outlet to exhaust the air. Column A is

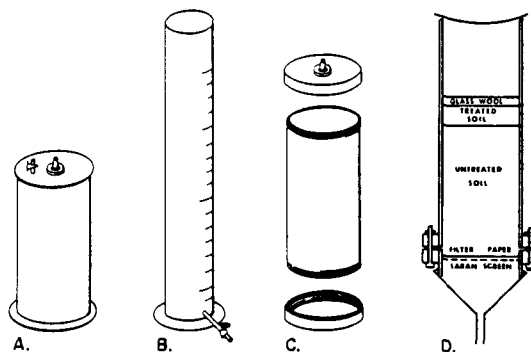


FIGURE 8. Diagrams of the different soil columns.

suitable for MSW-type leachates where anaerobic conditions must be maintained and constant fluxes are desired. It is most suited for heavy metal attenuation evaluation.

Column type B may be glass or plastic and is used for studies with strong acids and bases. Because the reaction between these wastes and soils is so rapid and corrosive, a soil depth of 30 to 36 cm is suggested. The waste fluids are applied at the top and allowed to migrate by gravity to the outlet at the bottom where the effluent is collected. No attempt is made to keep the system anaerobic, although simple alterations may be designed easily to exclude oxygen. Flow rates can be controlled by adjusting the head height of the fluid above the soil.

Column C is constructed for organic solvents. Column C is made of stainless steel; the steel caps are finely threaded for screw type closure with teflon gaskets at the top and bottom. Outlet and inlet ports are arranged at both ends for influent and effluent movement through the soil. The dimensions are similar to Column A, as is the method of operation. Iron is not adaptable for all organic solvents, therefore, boron glass columns such as D may be constructed.

Column D may be glass or plastic or lucite with the soil column packed over glass wool or another appropriate inert material. The depth of soil begins at the plane of size restriction and may extend to a level of 36 cm with an I.D. of 10 to 12 cm. Capping with a ground-glass joint at the top for further modification can provide volatilization control often needed with organic-solvent work. This type of column has been effectively used for microbial degradation evaluations, organic wastes, and radioisotope movement.¹⁹

A number of innovations of aerobic biodegradation columns have appeared in the literature over the early and middle 20th century.^{81-83,89} In many of these studies heavy isotopes and radioisotopes (e.g., ^3H , ^{14}C , ^{15}N , ^{32}P , ^{58}Fe , ^{42}Ca , ^{89}Sr , ^{89}Sr - ^{90}Y) were incorporated into biological materials. The organic residues may be mixed with known amounts of soil and placed in a layer on the soil surface of the columns. Biodegradation is followed by recovering the isotope or other desired constituent in the leachate as the soil columns are irrigated periodically with known amounts of water, chelate solutions, and other appropriate liquids. The columns can be segmented and movement of the constituent and/or pollutant determined on successive soil segments, as reviewed by Fuller.¹⁹

2. The Complete Soil-Column System

The diagram represented in Figure 9 depicts a simple gravity feed for waste streams of Category A (dilute aqueous solutions). The fluids are pumped by CO_2 pressure from a cylinder to a constant head device from a bulk reservoir. The fluid (such as MSW leachate) is then distributed to the soil columns (type A of Figure 8). Each soil column requires height adjustment to unify flow rates among the columns because of differences in packing and soil type.

Testing equipment diagrammed in Figure 10 may be used for the same purpose as that

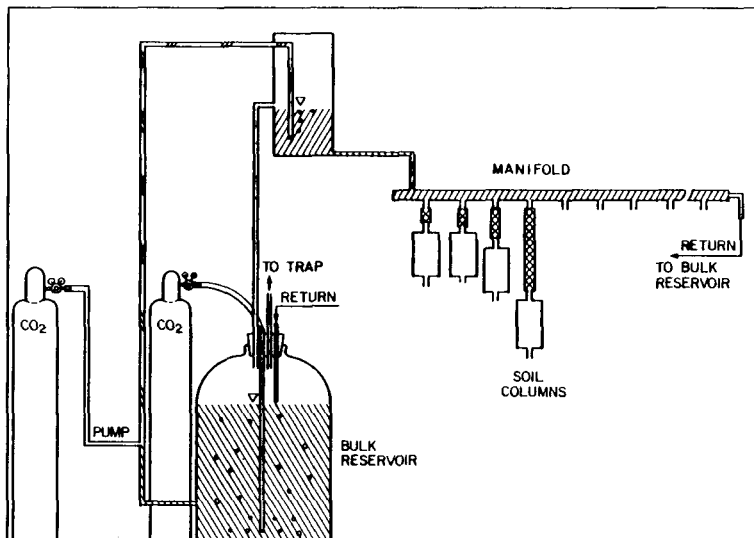


FIGURE 9. The soil-column system used to study attenuation of landfill leachate metals with gravity feed.

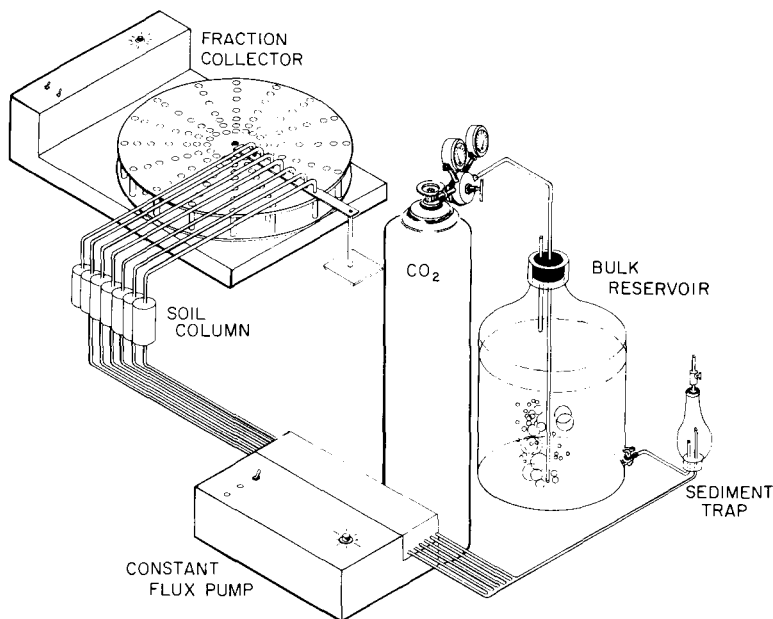


FIGURE 10. Diagram of the soil-column system using the peristaltic pump and fraction collector.

of Figure 9, but is more automated. In this system a peristaltic pump is installed to deliver precise flow rates (fluxes) and a fraction collector is used to automatically collect samples at predetermined, precise times of delivery.

Soil column equipment used to evaluate the effects of solvents on soil retention of pollutants is illustrated in Figure 11. This is a modification of Figure 10. Because the plastic tubing in the peristaltic pump is subject to undesirable alterations by many organic solvents, water is used as a displacement liquid. It in turn displaces the solvent through an air displacement process and the solvent then passes into the soil column as influent.

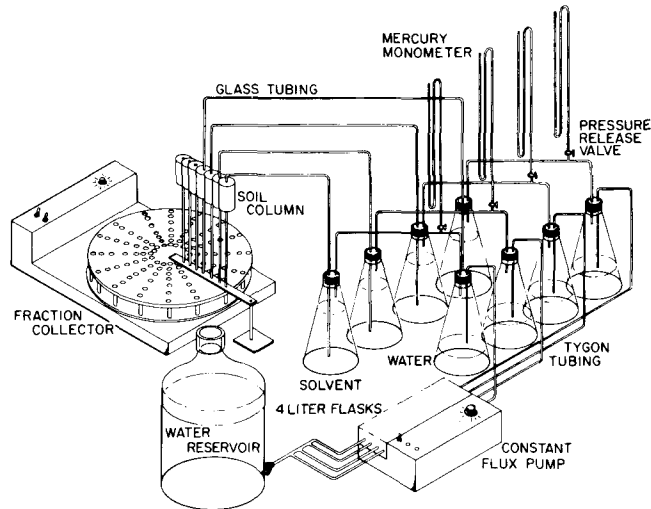


FIGURE 11. Soil-column system used to evaluate effects of organic solvents on soil retention of pollutants.

E. Application of Influent to Soil Column

Application of the influent may be either under aerobic or anaerobic conditions. The latter requires most sophisticated equipment since oxygen (air) must be excluded.

1. Anaerobic (Anoxic)

The apparatus illustrated in Figures 9, 10, and 11 are designed to exclude oxygen of air. Air is prevented from entering the system by continuously purging with O_2 free gases. Our experience shows compressed CO_2 works well and does not introduce traces of O_2 often found in other commercial tank gases, such as nitrogen (N_2) and argon (Ar), and does not introduce excesses of gases not naturally present in abundance in anaerobic biodegradable systems.⁹⁰ The equipment and technique are designed to accommodate dilute aqueous waste streams and aqueous leachates such as those from municipal solid wastes. Should these waste streams contain volatile organic solvents or other volatiles, a trap modification is necessary should it be desired to account for all of the organics or to avoid escape of toxic substances. Traps can be installed at almost any location in the train.

2. Aerobic (Oxic)

All of the equipment illustrated (Figures 9, 10, and 11) can be operated under aerobic conditions either by (1) aerating the reservoirs of influent waste fluids before they enter the column of soil or by (2) venting the columns. It must be kept in mind, however, that aeration of most aqueous wastes, particularly those generated under anaerobic conditions such as MSW leachates, results in immediate precipitation of some soluble constituents.^{5,17} This can defeat the purpose of evaluation of attenuation as represented under some natural environments. The soil-liquid interfaces of most organic-containing disposals are anaerobic. Evaluation by the soil column technique is concerned with migration of pollutants that enter the soil in a soluble state.

Any of the soil columns of Figure 8, but C, may be made of glass or plastic, or stainless steel. Waste streams of strong acids and bases are examples of aerobic systems that require glass columns. Strong acids and bases keep the pollutants, which they contain, in a soluble state in the presence of air. The stainless steel column C is used most effectively for organic solvents.

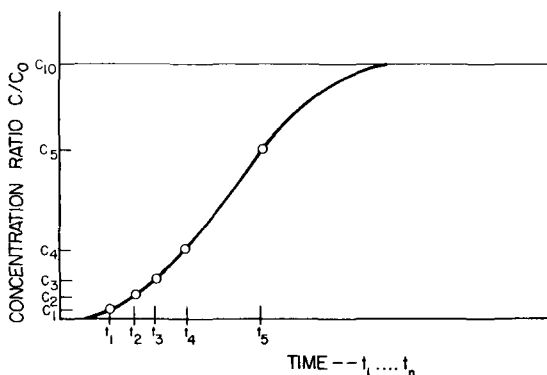


FIGURE 12. An example of a typical breakthrough curve for movement of pollutants through soils.

F. Collection of Effluent from Soil Column

Collection of effluent from the soil column can be accomplished automatically, by using a fraction collector set at regular time intervals, or manually. The latter can be a nuisance, particularly during off work hours if frequent time intervals are required.

Collecting samples anaerobically is more difficult than aerobically and requires special equipment. Some use the mineral oil displacement procedure when aqueous leachates are studied for heavy metal pollutant attenuation. Another method is to use deflated teflon bags that fill with minimum resistance.

Collecting aerobically into plastic or glass containers often requires the effluent to be maintained acidic to prevent precipitate formation. A few milliliters of 1 *N* HNO₃ (depending on anticipated volume of effluent) may be used effectively. In the 5 × 12 cm soil columns a convenient displacement rate is one half a pore volume displacement per day. One pore volume (PV) represents a volume of fluid equivalent to volume of pores in the column. Many soils with significant clay that are tightly packed into the columns do not permit this rate of flow without exertion of some pressure. Usually, however, soils can be packed uniformly to achieve a slow rate of flow with a small head of influent or by some pressure exerted by a peristaltic pump.

Effluent is collected until breakthrough of pollutant takes place. Breakthrough is defined in terms of the ratio c/c_0 , where c is the concentration of the pollutant in the effluent appearing at the soil column exit and c_0 is the concentration of the pollutant in the influent at the soil-column intake. Breakthrough takes place when c/c_0 approaches 1 (i.e., the concentration(s) of pollutant(s) in the effluent approaches that of the influent pollutant(s) of the waste stream). It is assumed that at this point the soil has reached its full capacity to retain the pollutant. There is some merit in designating 50% or 0.5 breakthrough point as a useful figure with which to work for predictive purposes. Typical breakthrough curves are illustrated in Figures 12 and 13. The full breakthrough ($c/c_0 = 1.0$) is necessary for data adaptation to the Lapidus and Amundson²⁰ and other simulation models, such as the Error Function, for prediction of pollutant migration.

G. Collecting and Processing Data

Predicting pollutant movement through soils is dependent on determination of pertinent characteristics of the three major disposal environmental components: soils, fluids (waste streams, leachates, solvents, oils, acids, and bases), and the pollutant itself (heavy metals, solvent, organic compounds, etc.). The soil-column technique requires that only the readily measurable properties of the disposal system be determined. Simplicity and accuracy are

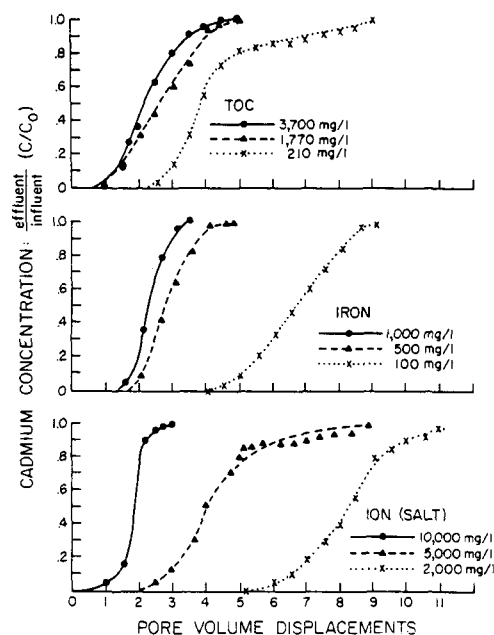


FIGURE 13. Cadmium concentration in soil-column effluents comparing migration rates through *Ava si c l* as related to different landfill leachates at a flux of 5 cm/day. (From Fuller, W. H. and Alesii, B. A., *Environ. Sci. Health*, A14, 587, 1979. With permission.)

essential to the acceptability, practicability, and universality of the soil column method. Although somewhat redundant, following is a review of data needed.

1. Soils Data

The kinds of soil information most useful for prediction of pollutant movement are

Physical	Chemical
Soil type	pH
Particle size distribution	Particle surface area
X-ray analysis of the <2- μ m clay	Soluble salts
Amount of soil in soil column	Soil organic matter
Bulk density	Lime content
Particle density	Hydrous oxides of Fe
Soil porosity	Cation exchange capacity

2. Transport Fluid Data

The kind of transport fluid data most useful for predicting pollutant movement are

- Total organic carbon
- Soluble common salts (Na^+ , K^+ , Ca^{++} , Mg^{++})
- pH
- Total solids
- Polar or nonpolar solvent
- Toxicity level of volatile constituents
- Concentration of solvent if in aqueous solution
- Associated potential pollutants (e.g., heavy metal in aqueous or solvent transport system)

3. Soil-Column Data

The kinds of soil-column data most desirable in the predicting pollutant movement through soils are

- Volume of influent used
- Volume of effluent recovered
- Flow rates
- Chemical characteristics of influent
- Properties of specific potential pollutant(s) in the waste stream
- Swelling of the soil
- Gas formation
- Rate of advance of wetting front

Again it should be emphasized that the data on the soil, the transport system, and the soil column suggested here as being desirable are well in excess of the data absolutely necessary for attenuation or pollutant movement predictions.

4. Breakthrough Curves and Statistical Analyses

Breakthrough curves are developed by plotting c/c_0 against volume of effluent discharging from the column of soil in terms of soil-column pore-volume displacement. Breakthrough is achieved when the ratio $c/c_0 = 1$. At this point, the full capacity of the soil to retain soluble pollutants is reached, as observed earlier regarding Figure 12 and in an actual study of Cd movement through soil (Figure 13). The effect of different qualities of leachate (to c, salt, and iron) on rate of Cd movement is also illustrated.

There are many properties of the soil, characteristic of the solution transport system, and reactions of the specific pollutant that determine the shape of the breakthrough curve. Ideally, only a few of these characteristics are primarily responsible or they parallel other properties for the rate of movement that determines the final shape and breakthrough point.

Miscible displacement theories and experimental data indicate the solute profile is not one of piston displacement, but rather is a smooth distribution of concentrations.⁹¹ In addition, the translation of different relative concentrations appear to be at different rates (Figure 14). Since the velocity of a particular concentration is a function of distance, z , it follows that the shape of the experimental breakthrough curve will also be a function of z . However, the figure depicts that for $z = 10$ cm, the velocity of a particular relative concentration approaches an asymptotic value, i.e., steady state velocity for any relative concentration has been achieved by a depth of 10 cm. This is not absolutely true, but for many systems is a valid approximation.

An analysis of variance can be employed to identify the most pertinent factors responsible for controlling pollutant movement and attenuation. For example, a great number of measurable soil variables, including the total elemental analysis, exchangeable cations, anions, total Na, K, Ca, and Mg, salts, pH, sand, silt, clay, and hydrous oxides of Fe and total Mn was studied in relation to heavy metal attenuation from MSW leachates.¹⁸ Twenty single variables and over 120 cross products and possible interactions were tested in a regression equation.⁹² Correlations were most prominent for clay, silt, hydrous oxides of Fe, Mn, and surface area.

The transport fluid properties most essential for predicting attenuation or migration of pollutants were found to be total organic carbon (TOC), total soluble inorganic salts (Na, K, Ca, and Mg), and pH.

H. Predicting Pollutant Movement

The single goal in the disposal of waste is to insure the containment of potential envi-

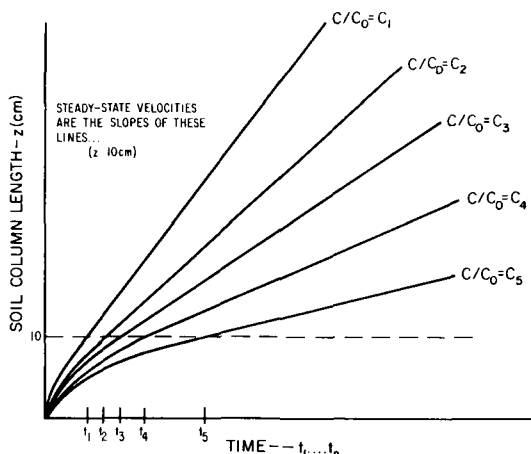


FIGURE 14. Trajectories of different relative concentrations (plot of $z = z(t)$, where $z = z(t)$ satisfies $c(t, z(t)) = C_i$, $i = 1, 2, 3, 4, 5$).

ronmental polluting constituents at the site. There are few guidelines and no standardized methods for estimating movement of pollutants through the most used material for disposal, the soil. Our ability to provide managers of land disposal operations with even the crudest quantitative procedure are lacking. The soil-column technique, therefore, was developed to provide a more quantitative basis for estimating pollutant movement through soils.

1. Direct Application of Breakthrough Data

When the soils are known and available and the transporting fluid is known, a series of soil columns may be established and breakthrough curves plotted from c/c_0 data and pore volume displacements. The migration rates then may be applied directly for prediction of rates of pollutant movement. By knowing the depth of soil to the water table, rainfall, and water infiltration rate, translocation of pollutants may be estimated directly from the breakthrough curves at the concentration sought for containment.

Another means of predicting pollutant migration rate is to rank the pollutants according to soil interactions as illustrated by Korte et al.⁹³ Although this method is more quantitative than the conceptual "model" of personal judgment, it too is a highly qualitative procedure though actual research data are used. Heavy metal soil interactions may be ranked (Figures 15 and 16) using prominent toxic waste elements, As, Be, Cd, Cr, Cu, Hg, Ni, Pb, Se, V, and Zn, with soils representing the major orders. Cations and anions are ranked separately because of differences in migration behavior in different soils. Changes in ordering of soils when going from cations to anions involve a higher rank for soils having lower pH values and/or higher free iron oxide contents. The soil environment in this example was strictly anaerobic and the leachate saturated flow conditions similar to those under a landfill operation. Predicted relationships for any situation with like soils can be found by using Figures 15 and 16 and typical attenuation curves as presented for each soil and a given element.⁹³

Those metals that form anions (As, Cr^{+6} , Se, V) (Figure 16) in the landfill leachate behave differently than those that form cations in the previous Figure 15. The anions are more pH independent and relate more to hydrous oxides of the soils than do the cations. Attenuation is relatively more efficient for soils lower in pH and/or higher in free oxides of iron. Lime is less effective with some anion retention than cation retention.

Soil-column data can provide yet another means of predicting pollutant retention by soils. An example of this is illustrated by heavy metal attenuation to develop breakthrough curves (e.g., c/c_0 at increasing pore volume displacements) for different soils with a single metal

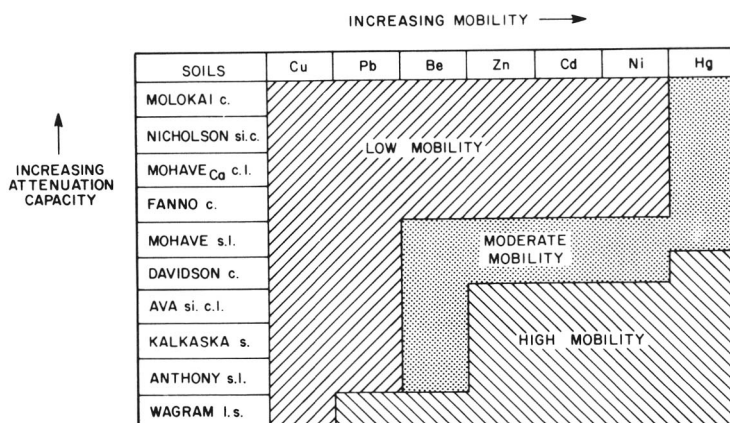


FIGURE 15. Relative mobility of cations through soil. (From Korte, N. E., Skopp, J., Fuller, W. H., Niebla, E. E., and Alesii, B. A., *Soil Sci.*, 122, 357, 1976. With permission.)

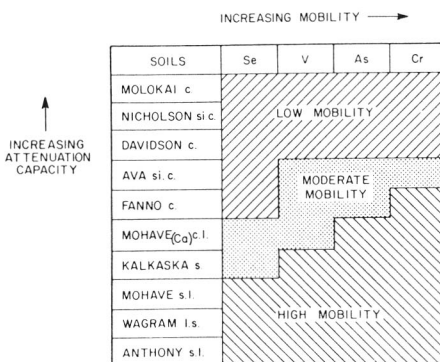


FIGURE 16. Relative mobility of anions through soil. (From Korte, N. E., Skopp, J., Fuller, W. H., Niebla, E. E., and Alesii, B. A., *Soil Sci.*, 122, 357, 1976. With permission.)

(e.g., Ni \times 4 soils) (Figure 17) and different metals with a single soil (e.g., Ava si c l \times Ni, Be, and Se) (Figure 18). These curves then may be used to construct a set of typical breakthrough curves (Figure 19). The different types of breakthrough curves for each soil and a given element are given an identification letter, A to E (Figure 19). The values of c/c_0 obtained from any one soil column correspond to one of the generalized curves in Figure 19. Weakly retained elements are represented by curves A and B. Complete breakthrough where $c/c_0 = 1$ occurs rapidly. The rise in pollutant concentration in the effluent of A begins earlier than B and breaks through earlier. In turn, B is more rapid than C, and so on. Curves C and D represent a large capacity of the soils to retain the pollutant or the pollutant disappears. Curve E is an example of an extreme situation of soil (clay) that did not permit the pollutant (metal) to pass through. This represents the situation where the soil has an extremely large capacity compared to the waste stream or the pollutant is nonconservative.

For further illustration, elution curves obtained from each soil column are coded in Table 5. Sandy soils (Wagram, Kalkaska, and Anthony) are identified most often with sharp breakthroughs. Clay soils (Nicholson and Molokai) demonstrate slow leakage and high

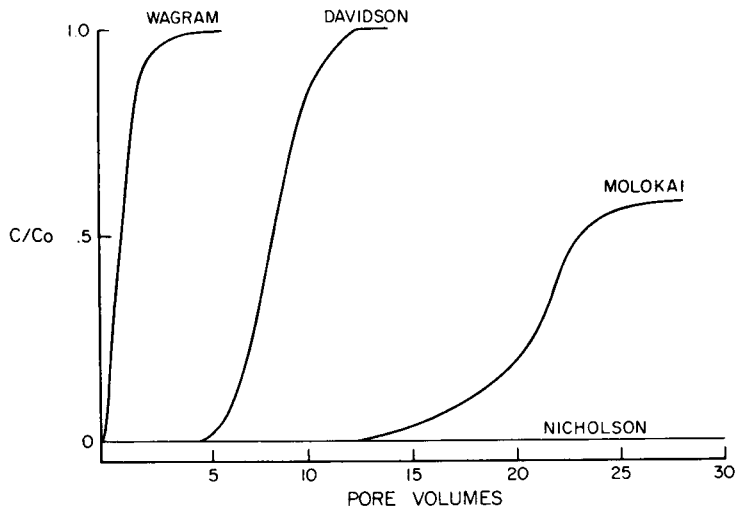


FIGURE 17. Relative migration of nickel through four diverse soils. (From Korte, N. E., Skopp, J., Fuller, W. H., Niebla, E. E., and Alesii, B. A., *Soil Sci.*, 122, 354, 1976. With permission.)

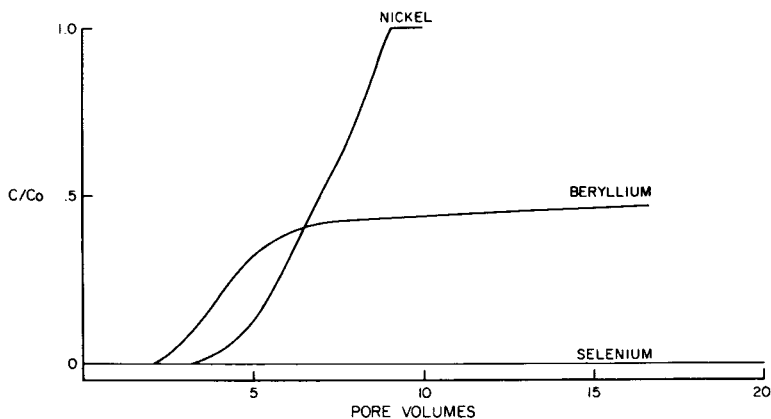


FIGURE 18. Relative migration of nickel, beryllium, and selenium through Ava silty clay loam. (From Korte, N. E., Skopp, J., Fuller, W. H., Niebla, E. E., and Alesii, B. A., *Soil Sci.*, 122, 353, 1976. With permission.)

retention. Mohave (Ca) cl is an exception for Cr (VI), but it contains free CaCO_3 (lime) and has a relatively high pH of 7.8, both of which factors decrease migration. Again, if it is desired to estimate, for disposal purposes, the attenuation characteristics of another soil or soil-like material at some other location or depth, for example, its characteristics can be compared with the characteristics of the most similar soil material used in this study.

Fortunately, heavy metal attenuation is not appreciably influenced by modest changes in solution flux through soil columns.⁹⁴ Although with relatively slower rates of flow of leachates there appears to be a tendency of some metals to breakthrough more slowly, attenuation of most heavy metals is not significantly changed. For example, only Al, Be, Cr(VI), and Fe(II) in MSW landfill leachates were found to be significantly (0.05) retained by reduced flux of several orders of magnitude (Figure 20).⁹⁴ Flux of several fold variation appears to be of little importance to breakthrough time for Cd, Ni, and Zn (Figure 21).⁹⁴

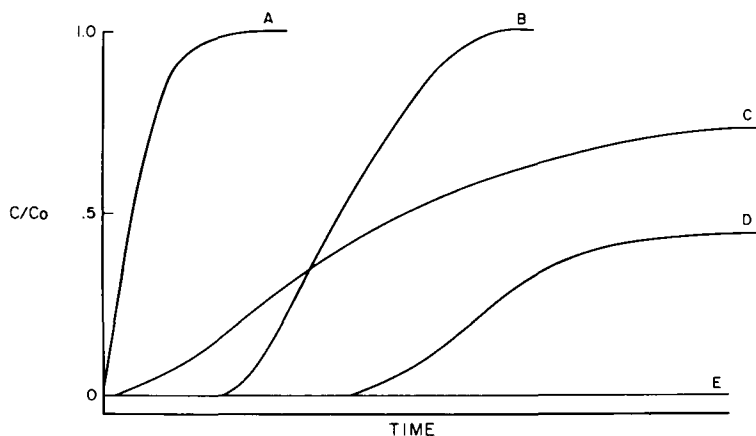


FIGURE 19. Types of breakthrough curves generated by the soil-column technique. (From Korte, N. E., Skopp, J., Fuller, W. H., Niebla, E. E., and Alesii, B. A., *Soil Sci.*, 122, 354, 1976. With permission.)

Table 5
DESIGNATION SHOWING TYPE OF CURVE GENERATED FROM EACH COLUMN

Soil	As	Be	Cd	Cr	Cu	Hg	Ni	Pb	Se	V	Zn
Davidson c	C	D	C	E	E	C	B	E	E	E	D
Molokai c	E	E	E	E	E	D	D	E	E	E	E
Nicholson si c l	E	E	E	D	E	B-C	E	E	E	E	D
Fanno c	C	E	E	C	E	C	E	E	E	D	C
Mohave Ca c	E	E	E	A	E	D	E	E	C	E	E
Chalmers si c l	C	D	D	C	E	D	D-E	E	E	C	D
Ava Si c l	C	D	A	C	D	B-C	A	D	E	B	A-B
Anthony s l	A	D	A	A	D	A	A	D	C	A	B
Mohave s l	B	D	D	A	E	B	C	E	C	B	B
Kalkaska s l	C	D	C	C	E	C	B	E	C	D	B
Wagram s l	A	C	A	A	E	A	A	B	D	A	A

From Fuller, W. H., Investigation of Landfill Leachate Pollutant Attenuation by Soils, EPA-600/21-78-158, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1978, 61.

2. Development of Models for Prediction

According to Maisel and Gnugnoli, a model provides a simplified analogy for a natural phenomenon.⁹⁵ For our purpose, a model can be defined as a simplified representation of an actual waste disposal system. Briefly, three kinds of models relate to prediction of pollutant movement:

1. A conceptual model, which is the oldest and is strictly based on personal judgment
2. A physical model, which is a scaled-down version of the actual system
3. A simulation mathematical model

Mathematical models offer the most promising method of assessing the waste disposal system. The mathematical model of a system is a logical model which is usually developed by considering the physicochemical characteristics of the whole system. Through simulation, the model can describe the system in its present state or be used to evaluate its future behavior

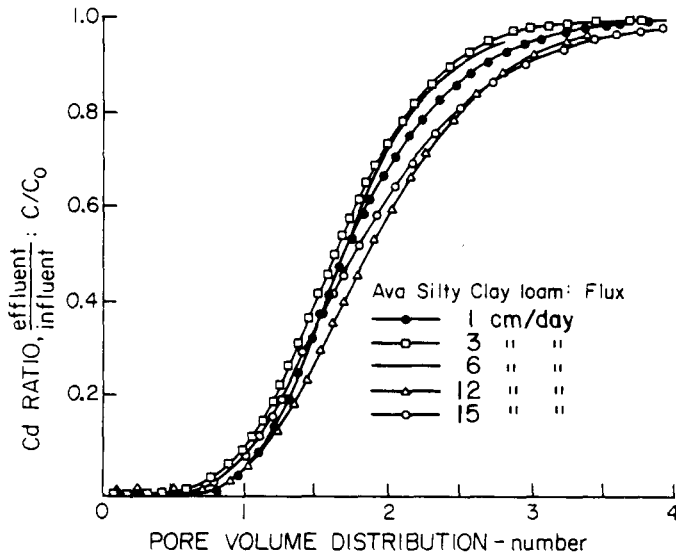


FIGURE 20. Effect of flux of municipal solid waste landfill leachate through Fanno clay comparing the retention of cadmium and chromium. (From Alesii, B. A., Fuller, W. H., and Boyle, M., *J. Environ. Qual.*, 9, 119, 1980. With permission.)

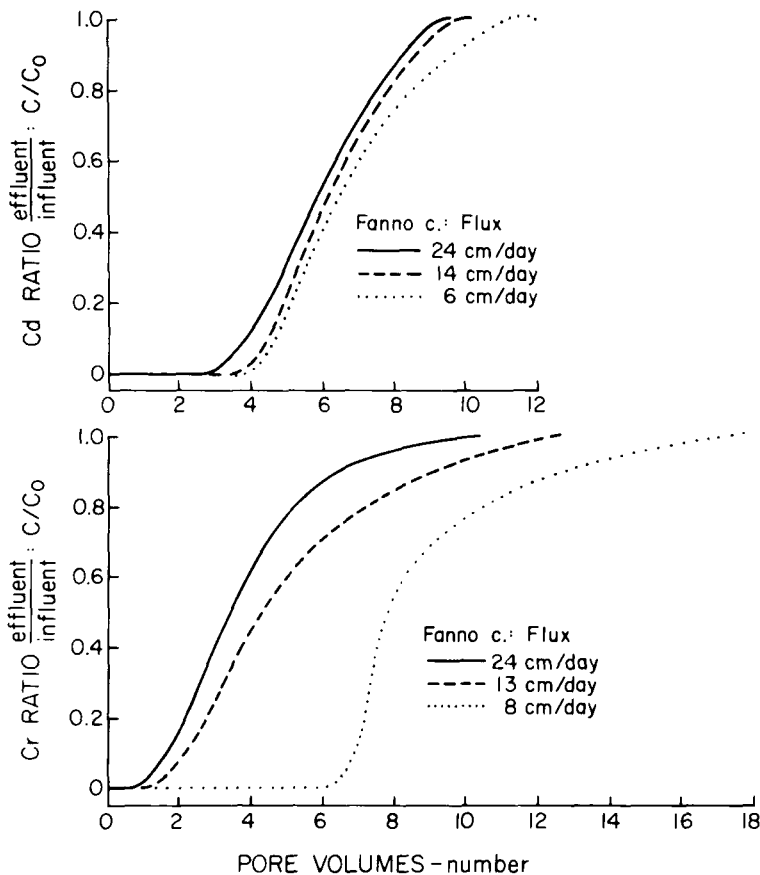


FIGURE 21. Effect of flux at different rates, on attenuation of cadmium contained in MSW leachate through Ava silty clay loam. (From Alesii, B. A., Fuller, W. H., and Boyle, M., *J. Environ. Qual.*, 9, 119, 1980. With permission.)

or status.⁹⁵ The methods and techniques used for arriving at the final predictive movement of certain pollutants through soils, and the models used, are presented in Chapter 5.

I. Advantages and Limitations

Because the soil is disturbed, certain numerous gross natural variations of the soil habitat (such as cracks, subsoil restrictive layers, texture stratifications, excessively compacted layers, root and rodent channels, and pipings, etc.) are not known and, therefore, cannot be included in the interpretation of the column results. Such natural heterogeneities in the physical character of the soil area can exert a dominant influence on pollutant movement making predictions from the soil-column method, or any other soil method which involves disturbed soil samples, unrealistic. As many of the natural soil and land characteristics as possible should be identified and evaluated independently of the soil-column test. In many instances field conditions are so variable there is no way to assess their impact on retention of pollutants. Briefly, the soil-column limitations and advantages are

1. Limitations

- The method evaluates only the soil's capacity to attenuate or retain pollutants and may not reflect actual field conditions where the many natural soil variations are not or cannot be identified. In fact, it should be kept in mind that the method is not designed to characterize the natural landscape variabilities. This must be done independently.
- Sometimes the actual transport system (e.g., leachate, solvent, and waste stream) cannot be identified prior to disposal. In order to obtain the most reliable quantitative evaluation of pollutant movement, the actual transport system needs to be known.
- The method generally overpredicts, i.e., it predicts a greater rate of movement than occurs under natural conditions. Many natural, unknown phenomena such as dehydration, aging, coprecipitation reactions, and biological fixation occur at the disposal site that cannot be fully identified or evaluated.
- By necessity, extrapolations to large times and distances are beyond the scope of the experiments. (However, alternative quantitative predictive tools are nonexistent.)

2. Advantages

- The method is less complicated than many alternatives.
- It does not rely on identification of all attenuation mechanisms. It is a simple input/output system.
- It is responsive to changes in concentrations as the fluid undergoes alteration during percolation through the soil. Unlike batch methods, therefore, the original transport fluid does not contact the whole soil, but more closely mimics natural field conditions.
- Soil structure, pore-space distribution, the tortuous capillaries, and diffusion phenomena all become a part of the column method that gives the technique a more field-realistic representation than a batch-type method.
- Compared with field studies, that which can be confounded by a great number of uncontrollable variables, the method evaluates the soil alone, free of measurable natural field anomalies that shift and change from location to location, often within short distances.
- The length of the soil column is such that the data generated can be projected while approaching a steady state. Therefore, predictions can be applied to any depth of soil or distance or time of travel of the pollutant.
- Actual soils from the proposed or selected site are used and, if possible, the actual leachate or waste stream is involved.
- The soil column method is ideally adapted for disposal-site, soil-liner evaluation.
- Several constituents, such as several metals (Cd, Zn, and Ni), can be evaluated at one time in a single transport system.

- The method is easily adapted to mathematical modeling for the ready establishment of universal prediction equations simplified enough for field use with a minimum of mathematical computation.

REFERENCES

1. U.S. Environmental Protection Agency, Remedial Action at Waste Disposal Sites, EPA-625/6-82/006, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1983, 497.
2. **O'Donnell, D. F., Alesii, B. A., Artiola-Fortuny, J., and Fuller, W. H.**, Predicting cadmium movement through soils as influenced by leachate characteristics, in Management of Gas and Leachate in Landfills, Proc. 3rd Annu. Municipal Solid Waste Res. Symp., Banerji, S. K., Ed., EPA-600/9-77-026, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1977, 159.
3. **Fisher, S. A. and McGarvey, F. X.**, Laboratory evaluation of ion-exchange processes, in *Ion Exchange for Pollution Control*, Vol. 2, Calmon, C. and Gold, H., Eds., and Prober, R., Editor-in-Chief, CRC Press, Boca Raton, Fla., 1980, 99.
4. **Griffin, R. A. and Shimp, N. F.**, Attenuation of Pollutants in Municipal Landfill Leachate by Clay Minerals, EPA-600/2-78-157, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1978, 146.
5. **Fuller, W. H.**, Investigation of Landfill Leachate Pollutant Attenuation by Soils, EPA-600/21-78-158, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1978, 219.
6. **Fuller, W. H.**, Methods for conducting soil column tests to predict pollutant movement, in Land Disposal: Hazardous Wastes, Proc. 8th Annu. Res. Symp., Shultz, D., Ed., EPA-600/9-82-002, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1982, 87.
7. **Van Genuchten, M. T.**, Simulation models and their application to landfill disposal siting: a review of current technology, in Land Disposal of Hazardous Wastes, Schultz, D. E., Proc. 4th Annu. Res. Symp., EPA-600/9-78-016, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1978, 191.
8. **Fuller, W. H., Amoozegar-Fard, A., and Carter, G. E.**, Predicting movement of selected metals in soils: application to disposal problems, in Municipal Solid Waste: Land Disposal, Proc. 5th Annu. Res. Symp., Schultz, D., Ed., EPA-600/9-79-023a, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1979, 358.
9. **Fuller, W. H., Amoozegar-Fard, A., Niebla, E. E., and Boyle, M.**, Influence of leachate quality on soil attenuation of metals, in Proc. 6th Annu. Res. Symp., Schultz, D., Ed., EPA-600/9-80-010, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1980, 108.
10. **Fuller, W. H., Amoozegar-Fard, A., Niebla, E. E., and Boyle, M.**, Behavior of Cd, Ni, and Zn in single and mixed combinations in landfill leachate, in Land Disposal: Hazardous Wastes, Proc. 7th Annu. Res. Symp., Schultz, D., Ed., EPA-600/9-81-026, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1981, 18.
11. **Allaway, W. H.**, Agronomic controls over the environmental cycling of trace elements, *Adv. Agron.*, 20, 265, 1968.
12. **Fuller, W. H.**, Water, Soil, and Crop Management Principles for the Control of Salts, University Ariz. Exp. Stn. Ext. Serv. Bull. A-42, 21, 1965.
13. **Lisk, D. J.**, Trace metals in soils, plants, and animals, *Adv. Agron.*, 24, 267, 1972.
14. **Walsh, L. M. and Beaton, J. D., Eds.**, *Soil Testing and Plant Analysis*, Soil Science Society of America, Madison, Wis., 1973, chaps. 2 and 3.
15. **Richards, R., Ed.**, *Saline and Alkali Soils*, U.S. Department of Agriculture Handbook. No. 60, U.S. Department of Agriculture, Washington, D.C., 1954, 160.
16. **Korte, N. E., Skopp, J. M., Niebla, E. E., and Fuller, W. H.**, A baseline study of trace metal elution from diverse soil types, *Water, Air, Soil Pollut.*, 5, 149, 1975.
17. **Korte, N. E., Skopp, J., Fuller, W. H., Niebla, E. E., and Alesii, B. A.**, Trace element movement in soils: influence of soil physical and chemical properties, *Soil Sci.*, 122, 350, 1976.
18. **Fuller, W. H. and Alesii, B. A.**, Behavior of municipal waste leachate. II. In soil, *Environ. Sci. Health*, A14, 559, 1979.
19. **Fuller, W. H.**, Predicting radioactive heavy metal movement through soil, in *Waste Management '83*, Proc. Waste Management Symp., Tucson, Ariz. University of Arizona, Tucson, 1983, 341.
20. **Lapidus, L. and Amundson, N. R.**, Mathematics of adsorption in beds. VI. The effect of longitudinal diffusion in ion exchange and chromatographic columns, *J. Phys. Chem.*, 56, 984, 152.

21. Davidson, J. M., Rao, P. S. C., and Ou, L.-T., Movement and biological degradation of large concentrations of selected pesticides in soils, in *Disposal of Hazardous Wastes*, Schultz, D., Ed., Proc. 6th Annu. Res. Symp., EPA-600/9-80-010, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1980, 93.
22. Waters, E. M., Gertscher, H. B., and Huff, J. E., Trichloroethylene. I. An Overview, *J. Toxicol. Environ. Health*, 2, 671, 1977.
23. Wilson, J. T., Enfield, C. G., Dunlap, W. J., Crosby, R. L., Foster, D. A., and Baskins, L. B., Transport and fate of selected organic pollutants in a sandy soil, *J. Environ. Qual.*, 10, 501, 1981.
24. Brown, K. W. and Associates, Inc., Hazardous Waste Land Treatment, EPA-SW-874, U.S. Environmental Protection Agency, OWWM, 1983, 974.
25. U.S. Environmental Protection Agency, Guidance Document, Surface Impoundments-Liner Systems, Final Cover, and Freeboard Control, draft, Office of Solid Waste, RCRA, Washington, D.C., 1981.
26. U.S. Environmental Protection Agency, Guidance Document, Landfill Designer-Liner Systems and Final Cover, draft, Office of Solid Waste, U.S. Environmental Protection Agency, RCRA, Washington, D.C., 1981.
27. Kilmer, V. J., The estimation of free iron oxides in soils, *Soil Sci. Soc. Am. Proc.*, 24, 520, 1960.
28. Heilman, M. D., Carter, D. L., and Gonzales, C. L., The ethylene glycol mono-ether ester (EGME) technique for determining soil surface area, *Soil Sci.*, 100, 409, 1965.
29. Bernas, B., A new method for decomposition and comprehensive analysis of silicates by atomic absorption spectrometry, *Anal. Chem.*, 11, 1682, 1968.
30. Black, C. A., Ed., *Methods of Soil Analysis*, Monograph No. 9., American Society of Agronomy, Madison, Wis., 1965, 770.
31. Ando, H., Suzuk, M., Fuma, K., and Wallec, B. L., Atomic absorption of arsenic in nitrogen (entrained air) - hydrogen flames, *Anal. Chem.*, 41, 1974, 1969.
32. U.S. Environmental Protection Agency, Methods for Chemical Analysis of Water and Wastes, EPA-625/6-74-003, U.S. Environmental Protection Agency, Washington, D.C., 1974, 298.
33. U.S. Environmental Protection Agency, Test Methods for Evaluating Solid Wastes: Physical and Chemical Methods, EPA SW-846, U.S. Environmental Protection Agency, 1980, chaps. 1 to 11.
34. American Public Health Association, American Water Works Association, and Water Pollution Control Federation, *Standard Methods for Examination of Water and Wastewater*, 15th ed., Washington, D.C., 1980, 1134.
35. Jackson, M. L., Soil clay mineralogy analysis, in *Soil Clay Mineralogy*, Rich, C. I. and Krinze, G. W., Eds., University of North Carolina Press, Chapel Hill, 1963, 245.
36. Day, D. R., Particle fractionation and particle-size analysis, in *Methods of Soil Analysis, Part 1*, Black, C. A., Ed., American Society of Agronomy, Madison, Wis., 1965, 545.
37. Blake, G. R., Bulk density, in *Methods in Soil Analysis, Part 1*, Black, C. A., Ed., American Society of Agronomy, Madison, Wis., 1965, 371.
38. Diamond, S., Pore size distribution in clays, *Clay Miner.*, 18, 7, 1970.
39. Vomacil, J. A., Porosity, in *Methods in Soil Analysis, Part 1*, Black, C. A., Ed., American Society of Agronomy, Madison, Wis., 1965, 299.
40. Pramer, D. and Bartha, R., Features of a flask and method for measuring the persistence and biological effects of pesticides in soil, *Soil Sci.*, 100, 1, 1965.
41. Beckman Instruments, Inc., Beckman Microton³⁰ System Operating Manual, Fullerton, Calif., 1982, chap. 1.
42. Casida, L. E., Jr., Microbial metabolic activity in soil as measured by dehydrogenase determinations, *Appl. Environ. Microb.*, 34, 630, 1982.
43. Casida, L. E., Jr., Klein, D. A., and Santoro, T., Soil dehydrogenase activity, *Soil Sci.*, 98, 371, 1964.
44. Stevenson, I. L., Dehydrogenase activity in soils, *Can. J. Microb.*, 5, 469, 1959.
45. Frankenberger, W. T. and Johansen, J. B., Influence of crude oil and refined petroleum products on soil dehydrogenase activity, *J. Environ. Qual.*, 11, 602, 1982.
46. Donnelly, K. C. and Brown, K. W., The development of laboratory and field studies to determine the fate of mutagenic compounds from land applied hazardous waste, in *Land Disposal: Hazardous Waste*, Proc. 7th Annu. Res. Symp., Shultz, D. W., Ed., EPA-600/9-81-0026, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1981, 224.
47. Epler, J. L., Toxicity of Leachates, U.S. EPA-600/2-80-057, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1980, 134.
48. Stanford, G. and DeMent, J. D., A method for measuring short-term nutrient absorption by plants. I. Phosphorous, *Soil Sci. Soc. Am. Proc.*, 21, 612, 1957.
49. Bullock, J. S., Johnson, G. V., Maier, R. H., and Fuller, W. H., An improved indicator for the determination of calcium in plant material, *Soil Sci. Soc. Am. Proc.*, 25, 515, 1961.
50. Dean, L. A. and Gledhill, V. H., Influence of soil moisture on phosphorus absorption as measured by an excised root technique, *Soil Sci.*, 82, 71, 1956.

51. **Davidson, J. M., Ou, Li-Tse, and Rao, P. S. C.**, Adsorption, movement, and biological degradation of high concentrations of selected pesticides in soils, in *Land Disposal of Hazardous Wastes*, Proc. 4th Annu. Res. Symp. EPA-600/9-78-016, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1978, 233.
52. **LeClerc, E. L., Leonard, W. H., and Clark, A. G.**, *Field Plot Technique*, 2nd ed., Burgess, Minneapolis, 1962, 373.
53. U.S. Environmental Protection Agency, *Interim Final Rule on Standards for Owners and Operators of Hazardous Waste Treatment, Storage and Disposal Facilities*, 40CFR, Part 264, U.S. Environmental Protection Agency, Washington, D.C., 1982 (Draft, Office of Solid Waste).
54. **Ely, R. L., Jr., Ed.**, Performance of Clay Caps and Liners for Disposal Facilities, Final Rep., U.S. EPA Contract No. 68-03-3147, Research Triangle Institute, Research Triangle Park, N.C., 1982, chaps. 1 to 11.
55. **Weber, J. B.**, Interaction of organic pesticides with particulate matter in aquatic and soil systems, in *Fate of Organic Pesticides in the Aquatic Environment*, American Chemical Society, Washington, D.C., 1972, 55.
56. **Skidmore, E. L. and Woodruff, N. P.**, Wind Erosion Forces in the United States and Their Use in Predicting Soil Loss, Agric. Handb. No. 346, Agriculture Research Service, U.S. Department of Agriculture, Washington, D.C., 1968, 26.
57. **Chepil, W. S. and Woodruff, N. P.**, The physics of wind erosion and its control, *Adv. Agron.*, 15, 211, 1963.
58. **Skidmore, E. L., Fisher, P. S., and Woodruff, N. P.**, Wind erosion equation: computer solution and application, *Soil Sci. Soc. Am. Proc.*, 34, 931, 1968.
59. U.S. Soil Conservation Service, *A Method for Estimating Volume and Rate of Runoff in Small Waterbeds*, SCS-TP-149, Washington, D.C., 1973, 35.
60. **Phillip, C. R. and Nathwani, I.**, Soil-waste Interactions: A State-of-the-Art Review, Solid Waste Management Rep., EP 5-3-EC-76-14, Environment Canada, Environmental Protection Service, Minister of Supply and Services Canada, Mississauga, Ontario, 1976, 214.
61. **Rovers, F. A., Moaij, H., and Faraquhar, G. J.**, Containment attenuation — dispersed soil studies, in *Residual Management by Land Disposal*, Fuller, W. H., Ed., Hazardous Waste Res. Symp., EPA-600/9-76-015, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1976, 224.
62. **Helling, C. S.**, Pesticide mobility in soils. I. Parameters of thin-layer chromatography, *Soil Sci. Soc. Am. Proc.*, 35, 735, 1971.
63. **Helling, C. S. and Turner, B. C.**, Pesticide mobility: determination in soil thin-layer chromatography, *Science*, 162, 562, 1968.
64. **Parizek, R. R. and Lane, B. E.**, Soil-water sampling using pan and deep pressure-vacuum lysimeter, *J. Hydrol.*, 11, 1, 1970.
65. **Tyler, D. D. and Thomas, G. W.**, Lysimeter measurements of nitrate and chloride losses and no-tillage corn, *J. Environ. Qual.*, 6, 63, 1977.
66. **Amoozegar-Fard, A., Fuller, W. H., and Warrick, A. W.**, An approach to predicting the movement of selected polluting metals in soils, *J. Environ. Qual.*, 13, 290, 1984.
67. **Amoozegar-Fard, A., Warrick, A. W., and Fuller, W. H.**, A simplified model for solute movement through soils, *Soil Sci. Soc. Am. J.*, 47, 1047, 1984.
68. **Fuller, W. H.**, Movement of Selected Metals, Asbestos, and Cyanide in Soil: Application to Waste Disposal, U.S. EPA-600/2-77-020, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977, 243.
69. **Bartlett, R. J. and James, B.**, Behavior of chromium in soils. III. Oxidation, *J. Environ. Qual.*, 8, 31, 1979.
70. **Matricon, Inc.**, *Lining of Waste Impoundments and Disposal Facilities*, EPA SW-870, OWWM, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1980, 385.
71. **Chian, E. S. K. and DeWalle, F. B.**, Evaluation of Leachate Treatment. I. Characterization of Leachate, EPA-600/2-77-186a, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1977, 210.
72. **Chian, E. S. K. and DeWalle, F. B.**, Evaluation of Leachate Treatment. II. Biological and Physical-Chemical Process, EPA-600/2-77-186b, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977, 245.
73. **Grubbs, D. M., Haynes, C. D., Hughes, T. H., and Stow, S. H.**, Compatibility of Subsurface Reservoirs with Injected Liquid Wastes, Rep. No. 721, National Resources Center, University of Alabama.
74. **Fuller, W. H., McCarthy, C., Alesii, B. A., and Niebla, E. E.**, Liners for disposal sites to retard migration of pollutants, in *Residual Management by Land Disposal*, Fuller, W. H., Ed., Proc. Hazardous Waste Res. Symp., EPA-600/9-76-105, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1976, 280.
75. **Fuller, W. H.**, *Soils of the Desert Southwest*, The University of Arizona Press, Tucson, 1975, 102.
76. **Fuller, W. H.**, *Management of Soils of the Southwest Desert*, The University of Arizona Press, Tucson, 1975, 195.

77. **Lindsay, W. L.**, *Chemical Equilibria in Soils*, John Wiley & Sons, 1979, chaps. 2 and 3.
78. **Schramm, M., Warrick, A. W., and Fuller, W. H.**, Permeability of soil to four organic solvents and water, *J. Environ. Qual.*, in press.
79. **Anderson, D. and Brown, K. W.**, Organic leachate effects on the permeability of clay liners, in *Land Disposal: Hazardous Wastes*, Shultz, D., Ed., Proc. 7th Annu. Res. Symp., EPA-600/9-81-026, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1981, 400.
80. **Sheets, P. J., Fuller, W. H., and Amoozegar-Fard, A.**, The effects of organic solvents on the movement of cadmium through soils, Abstr., *Am. Soc. Agron.*, 38, 1982.
81. **Hannapel, R. J., Fuller, W. H., Bosma, S., and Bullock, J. S.**, Phosphorus movement in a calcareous soil. I. Predominance of organic forms of phosphorus in phosphorus movement, *Soil Sci.*, 97, 350, 1964.
82. **Hannapel, R. J., Fuller, W. H., and Fox, R. H.**, Phosphorus movement in a calcareous soil. II. Soil microbial activity and organic phosphorus movement, *Soil Sci.*, 97, 421, 1964.
83. **Fuller, W. H. and Clark, K. G.**, Microbiological studies on ureaformaldehyde preparations, *Soil Sci. Soc. Am. Proc.*, 12, 198, 1947.
84. **Fuller, W. H., Cater, A. B., and McGeorge, W. T.**, Behavior of Nitrogenous Fertilizers in Alkaline Calcareous Soils. I. Nitrifying Characteristics of Some Organic Compounds Under Controlled Conditions, Univ. Ariz. Agric. Exp. Stn. Tech. Bull., 120, 451, 1950.
85. **Fuller, W. H. and Rogers, R. N.**, Utilization of phosphorus from barley residues, *Soil Sci.*, 74, 373, 1952.
86. **L'Annunziata, M. F. and Fuller, W. H.**, The chelation and movement of ^{89}Sr - ^{90}Sr (^{90}Y) in a calcareous soil, *Soil Sci.*, 105, 311, 1968.
87. **Fuller, W. H. and L'Annunziata, M. F.**, Movement of algal- and fungal-bound radiostrontium as chelate complexes in a calcareous soil, *Soil Sci.*, 107, 223, 1968.
88. **Hardcastle, J. E. and Fuller, W. H.**, Relative absorption of calcium and strontium by some desert soil fungi, *Chemosphere*, 2, 59, 1974.
89. **Amoozegar-Fard, A., Fuller, W. H., and Warrick, A. W.**, Migration of salt from feedlot waste as affected by moisture regime and aggregate size, *J. Environ. Qual.*, 4, 468, 1975.
90. **Korte, N. E., Niebla, E. E., and Fuller, W. H.**, The use of carbon dioxide in sampling and preserving natural leachates, *J. Water Pollut. Control Fed.*, 48, 959, 1976.
91. **Nielson, D. R. and Bigger, J. W.**, Miscible displacement. III. Theoretical considerations, *Soil Sci. Soc. Am. Proc.*, 26, 216, 1962.
92. **Efroymson, M. A.**, *Multiple Regression Analysis. Mathematical Methods for Digital Computers*, John Wiley & Sons, New York, 1960.
93. **Korte, N. E., Fuller, W. H., Niebla, E. E., Skopp, J., and Alesii, B. A.**, Trace element migration in soils: desorption of attenuated ions and effects of solution flux, in *Residual Management of Land Disposal*, Fuller, W. H., Ed., Proc. Hazardous Waste Res. Symp., EPA-600/9-76-15, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1976, 280.
94. **Fuller, W. H.**, The importance of soil attenuation for leachate control, in *Waste Management Technology. Resource and Energy Recovery*, Proc. 5th Natl. Cong., cosponsored by National Solid Waste Management Assoc. and U.S. Environmental Protection Agency, EPA SW-22P, Washington, D.C., 1977, 297.
95. **Maisel, H. and Gnugnoli, G.**, *Simulation of Discrete Stochastic Systems*, Sci. Research Assoc., Inc., Chicago, 1972, 465.

Chapter 5

MODELS FOR PREDICTING POLLUTANT MOVEMENT THROUGH SOIL

I. APPROACH

This chapter centers exclusively on modeling and the application of data derived from the soil columns for predicting pollutant movement through soils. Techniques of the soil-column procedure itself are presented in Chapter 4. Included is the application of soil attenuation data to the Lapidus-Amundson model for development of simple universal equations useful as field-oriented tools to aid in estimating pollutant movement through soils. In the search for predictive models other than those of Lapidus and Amundson (L-A), a simpler and more general Error Function Model, is introduced. Predictions for rate of metal movement through soil from municipal solid waste landfill-type leachates is equally effective by use of either model.

Because of the great variabilities associated with undisturbed soil and geologic materials, the estimation of pollutant migration under field conditions is difficult, expensive and time consuming. Functional data on migration for screening purposes may be obtained through the use of homogeneous soils in columns in the laboratory while avoiding the multitude of problems of field conditions. From these data, user-oriented predictive equations may then be developed and tested by field experimentation for further verification and necessary refinements. An approach, therefore, is to use soil-column test data in association with the concepts of an appropriate mathematical model for predictive purposes. Such an approach does not rule out the use of data gathered for the natural environment, in fact, field model validation is eventually of absolute necessity.

Before predictive designs for disposal of hazardous wastes can be established, the characteristics of the components of the disposal environment affecting constituent migration must be identified and evaluated. Quantification of the effects of soil and leachate properties on constituent movement through soil is essential to the development of refined mathematical models that will yield universal equations, to provide the predictive power for planning the most effective waste disposal on land. The three major components of the waste disposal environment that interact in pollutant migration have been identified previously in Chapter 4 as the transport system, the porous medium through which the fluids and pollutants flow, and the specific pollutant itself. Descriptive parameters must be identified and quantified for model development and predictive purposes.

The predictive technique may be divided for convenience into four steps, namely:

- Quantitative measurement of the influence of soil and leachate parameters (sand, silt, clay, free-FeO, and surface area for soil; and TOC, Fe, inorganic ion concentration, salts, and pH for leachate) on attenuation of selected pollutants alone and in multiple combinations through soils of typical orders.
- Match theoretical curves from a computer model with the actual data collected.
- Translate these parameters directly into migration rates for a particular pollutant, using the data curve patterns developed from measurable soil-leachate properties.
- Regress the metal velocities against the soil and leachate characteristics in such a way that the results will provide equations that describe a desired simple relationship of a user-oriented predictive tool (independent of computer) for waste disposal on land.

Mathematical models offer a promising approach for assessing waste disposal systems. Through simulation, the model can describe the system in its present state or be used to

evaluate its future behavior or status (simulation is a numerical technique for conducting imaginary experiments using mathematical and logical models that describe the biological, chemical and/or physical characteristics of the system).¹¹ The availability of high speed computers and the development of scientific and simulation programming languages have made mathematical modeling more attractive and popular than ever. For general modeling and simulation concepts see Maisel and Gnugnoli.¹¹

Models other than those associated with computer simulations are also useful. The most common and the oldest model available is strictly based on personal judgment and common sense. In selection of a suitable site for land disposal, the operator applies a "conceptual model" for the evaluation of many factors he (or she) keeps in mind as a result of experience. This sort of modeling is highly subjective and uses qualitative judgment. Therefore, the results involve human errors. In applying a conceptual model to a waste disposal system the operator might depend only on personal experience or combine his experience with actual physical-chemical characteristics of the site.

Physical models are also a possible means of evaluating a waste disposal system. By definition, a physical model is usually a scaled-down version of the actual system. However, the results obtained from such models must be adjusted before applying to the actual system. High cost and limited applicability of physical models make them unattractive for evaluating waste disposal sites or predicting rates of pollutant retention.

II. PREDICTIONS USING SOIL COLUMN DATA

A. Ranking of Pollutants According to Soil Interactions

One means of predicting pollutant migration rates is to rank the pollutants according to soil interactions as indicated previously in Figures 15 and 16. This method incorporates actual data into the prediction and is more quantitative than a simple conceptual model but still not sufficiently versatile.

B. Predictions Using Soil and Pollutant Breakthrough Curves

Still another example of predicting pollutant migration rate in soils was also illustrated in the last chapter (Figures 17, 18, and 19). Breakthrough curves for different soils with a single metal and different metals with a single soil form a basis for constructing a set of typical curves of pollutant (heavy metal) attenuation or migration rates. The curves are coded and matched with different soils and different elements oriented in a table (Table 5) of relative attenuation. Characteristics of soils at another location can be compared to the most similar soil used in this study in order to estimate attenuation characteristics of the material at the new location.

C. Predictions Using Soil Column Data with Mathematical Models

1. Miscible Displacement

The movement of liquids into soil can be divided into two general classes, miscible and immiscible displacement. The term miscible refers to two liquids which mix easily. Examples are fresh water and salty water or water and alcohol. Immiscible displacement, on the other hand, involve fluids which do not mix freely, such as oil and water. Here we consider only miscible displacement phenomena in general and the movement of solute including polluting elements, Cd, Ni, Zn, and Cr, in particular.

The theory of the movement of solutes through soils has been the subject of many investigations. Numerous solutions for associated boundary value problems are by van Genuchten.^{12,13} A review of the miscible displacement and solute flow in soils has been presented by Biggar and Nielsen.¹⁴ Many solute-flow studies are based on the principles used by Lapidus and Amundson.¹ Some investigators have looked at the displacement of

soil water by water of a different quality.¹⁵ Some have considered the adsorption of ions by the soil particles.¹⁶⁻¹⁸ Skopp and Warrick¹⁹ developed a two-phase model for miscible displacement to overcome the limitation caused by poor approximation of the adsorption-desorption process. Using a similar concept, van Genuchten and Wierenga²⁰ presented a model to describe the movement of solute through soils with lateral or intra-aggregate diffusion. Melamed et al.²¹ present a model for salt flow with a source-sink term. Another review of solute transport is by Amoozegar, et al.²²

2. Selection of a Mathematical Model

Generally speaking, a mathematical model describes the status of a system with respect to time and location within the system. However, the greatest responsibility of a model is usually that of prediction. Unfortunately, all mathematical models have limitations. Often times, the solution is not available in an analytical form. Numerical techniques must be employed which are costly and require high speed computers. Even if there is an analytical model, the solution to the model still may require tedious evaluations of integrals or functions. As a result, the available model might not be suitable for large times (i.e., 25, 50, or 100 years or more), or for very deep location in the profile.

All models require input data. A problem that is unavoidable is the inherent variability of physical and chemical properties of the soil. Use of the deterministic values of soil properties in a model (pore water velocity and apparent diffusion coefficient, for example) might not give the best estimate of the actual field conditions.²²⁻²³ Ideally, any characteristics of the site must be determined using an adequate number of sample replications. For more information about variability see Warrick and Nielsen.²⁴

III. THE LAPIDUS-AMUNDSON MODEL

In selecting a mathematical model for predicting purposes, the major features of the system must be simulated. At the same time the model must be simple and have a solution that does not require excessive computer time.²³ One such model is based on the solution of Lapidus and Amundson.¹

A. The Equation

The differential equation describing the movement of pollutant solutes is taken as:

$$\frac{\partial c}{\partial t} + \frac{1}{\theta_v} \frac{\partial n}{\partial t} = D \frac{\partial^2 c}{\partial z^2} - v \frac{\partial c}{\partial z} \quad (1)$$

where

- c = concentration in soil solution (Fundamental dimensions M/L³)
- v = convective (pore water) velocity (L/T)
- D = apparent diffusion coefficient (L²/T)
- Θ_v = volumetric water content of soil (L³/L³)
- n = amount adsorbed per unit volume of soil (M/L³)
- z = vertical distance (L)
- t = time (T)

The adsorption rate (i.e. $\partial n / \partial t$) is assumed to be described as a first order reaction:

$$\partial n / \partial t = K_1 c - K_2 n \quad (2)$$

This implies that the rate of adsorption of the pollutant by soil is finite. The parameters K_1 and K_2 are forward and backward reaction terms (Dimensions $1/T$), respectively.

Further, it is assumed that the initial concentration of the pollutant in the soil solution and the amount of pollutant adsorbed is zero. Then at time zero, a solution having a pollutant concentration of c_o enters the system. The appropriate initial and boundary conditions are

$$\left. \begin{array}{l} c = 0 \\ n = 0 \end{array} \right\} , \quad t = 0 , \quad z > 0 \quad (3a)$$

and

$$c = c_o , \quad t > 0 , \quad z = 0 \quad (3b)$$

when c_o is the steady input concentration of the pollutant.

The solution to equations (1) and (2) subject to initial and boundary conditions (3a) and (3b) is

$$c/c_o = \exp(vz/2D)[F(t) + K_2 \int_0^t F(\tau) d\tau] \quad (4)$$

where

$$F(t) = [\exp(-K_2 t)] \int_0^t \{I_o [2\sqrt{K_1 K_2 \beta(t - \beta)/\theta_v}] \exp[-(z^2/4D\beta + \beta d)] \cdot [z/2\sqrt{\pi D\beta^3}]\} d\beta \quad (5)$$

with

$$d = v^2/4D + K_1/\theta_v - K_2$$

I_o is the modified Bessel function of the first kind of zero order. The term c/c_o is the relative concentration (i.e., the concentration c divided by the influent concentration, c_o) and varies between zero and one.

In Equation (4), c/c_o is a function of z , t , θ_v , v , D , K_1 and K_2 . Of the above, z , t , v and θ_v are either measured parameters of the system or have some expected or desired values for prediction purposes. On the other hand D , K_1 and K_2 are not easily measurable.

The Lapidus-Amundson model was formulated to describe the effect of longitudinal diffusion in ion exchange and chromatographic columns, where the chemical and physical parameters are uniform and well controlled; and the system is relatively simple. In a soil-leachate system, the number of parameters increases greatly, and their interrelationships are much more complex. Here the Lapidus-Amundson model is used to lump all unknown or nonspecified parameters into three unknowns, D , K_1 , K_2 , which can be determined from the experimental data as described below. It would be impossible to determine the spatial interrelation between all the different physical and chemical sites in the soil-leachate system. By applying the Lapidus-Amundson model, the net effect of the chemical nature of the leachate on the forward and backward reaction rates at a multitude of different adsorption sites is combined into effective forward and backward reaction rates for the particular conditions of the soil-leachate system in the experiment. Similarly, an effective diffusion coefficient is determined, or a diffusion-dispersion coefficient since the effects of diffusion-dispersion combine in one variable.

B. Parameter Estimation

One of the major problems using mathematical models in general and the Lapidus-Amundson model in particular is that of estimating meaningful values for the unknown parameters. The three parameters D , K_1 and K_2 appear in a nonlinear form and their estimation is complicated. In addition, although Equation (4) is an analytical solution to Equation (1), the integrals have no closed form solution, and therefore must be evaluated numerically.

1. General Procedure

A variable metric minimization routine²⁵ is used to find the location of the minimum of the sum of the squares of the differences between the experimental values Y_i and predicted values $C_i = c_i/c_0$.

$$SSD = \sum_{i=1}^N [Y_i - C_i]^2 \quad (6)$$

Eleven points ($Y_i = c/c_0 = 0.02, 0.1, 0.2, \dots, 0.9$, and 0.98 ; for $i = 1, \dots, 11$ respectively) from the experimentally determined breakthrough curve are used for comparison. The choice of 11 points is somewhat arbitrary, but allows for a reasonable fit without too much emphasis on small clusters of data. This minimization procedure requires the knowledge of the first derivative of $c(z,t)$ in Equation 4 with respect to D , K_1 and K_2 .

2. Error of Calculations

The modified Bessel function I_0 and its derivative I_1 (modified Bessel function of the first kind and first order) are approximated by polynomials with negligible error.²⁶ Both functions, I_0 and I_1 , increase rapidly as their argument increases. Similarly, when the argument of the exponential function is negative, the magnitude of the exponential term in Equation 4 and other equations decreases rapidly as the absolute value of the argument increases.

A source of error is the evaluation of the double integral in Equation 4. For most cases a 24 point Gauss-Legendre quadrature may be used.²³ For each calculation of c/c_0 , there would be 24×24 or 576 evaluations of the integrand. For cases where the breakthrough curve is delayed, in other words where t is rather large (i.e., the interval of the integration, 0 to t , is large) more accurate evaluation of the integral is needed. For such cases a 40 point or even a 64 point quadrature can be used. Using the iterative least square procedure to estimate D , K_1 and K_2 the cost of estimation will increase drastically as the accuracy of calculation increases. In addition, for the cases where the breakthrough curve does not appear early or where the breakthrough curve extends over a long period of time (say over 50 days for a 10-cm column), the numerical integration is overly tedious.

The error of integration by Gauss' formula for time t is

$$R_n = \frac{t^{2n+1} (n!)^4}{(2n+1) (2n)! 3} f^{2n}(\tau) \quad , \quad 0 < \tau < t \quad (7)$$

where n is the number of points in the Gauss' formula and f^{2n} in the $2n$ th derivative of the integrand.

C. Vertical Movement of Polluting Metals

The downward movement of a polluting metal through soil can be expressed in terms of the vertical velocity of a relative concentration. It is assumed that the velocity of each relative concentration reaches a constant value within a relatively short distance from the point of pollution. This constant value is referred to as the steady state velocity of that relative concentration.

The value of the steady state velocity and the depth at which steady state velocity is achieved depend on the estimated values of D , K_1 and K_2 which in turn are dependent on the soil-leachate metal properties. Analytically the velocity can be evaluated from Equation 4 by

$$(\partial z / \partial t)_c = -(\partial c / \partial t)_z / (\partial c / \partial z)_t \quad (8)$$

From a practical standpoint, Equation 8 is unwieldy and an alternative method for evaluated velocity was developed as described in the next section.

D. Velocity Estimation Procedure

The steady state velocity of relative concentrations 0.1, 0.2, . . . , 0.9 for each metal-soil-leachate combination may be calculated through the steps described below. The example presented here is for the movement of Cd present in the leachate containing 2600 mg L⁻¹ TOC and 1600 mg L⁻¹ salts through Anthony sandy loam.

- a. Experimental breakthrough curves are matched against the theoretical breakthrough curve obtained by the L-A model (Equation 4) and the parameters D , K_1 and K_2 estimated.
- b. Using the estimated parameters in the L-A model, values of c/c_o are calculated for 40 values of depth z ranging from 2 cm to 100 cm, and 10 to 20 values of time t ranging from 0.2 days to over 200 days depending on the metal, soil and leachate under consideration. The results were stored in a two-dimensional array such as Table 1.
- c. Using a cubic spline function a smooth curve is fitted to the values for each time, i.e., expressing z in terms of c/c_o .²⁷ Figure 1 shows the calculated values and the fitted smooth curve for $t = 0.1$ to 30 days. Then for each time the corresponding value of z may be calculated for $c/c_o = 0.1, 0.2, \dots, 0.9$. Results should be stored in a two-dimensional array such as Table 2, and values of z vs. t for each one of the c/c_o 's plotted, Figure 2.
- d. The curves z vs. t for each c/c_o are inspected visually for linearity for large values of t and z . If each curve has an asymptote, an equation for a line is fitted to the linear portion of the curve. If the linear regression equation has a coefficient of determination, r^2 , greater than 0.99, the regression coefficient of the equation (the slope of the line z vs. t) is taken as the steady state velocity of that relative concentration.
- e. If any one of the nine curves do not have an asymptote or if the r^2 of the regression is less than 0.99, steps b-d are repeated using a 40- or even 64-point quadrature in the L-A model.
- f. After repeating the calculations, if the results are not satisfactory the D , K_1 and K_2 are inspected, and the experimental breakthrough curve verified against the theoretical curve. The case must not be considered for development of predictive equations if the results at step d are not satisfactory.

For convenience, steps a-d are performed on the computer.

E. Development of Equations for Prediction

1. Multiple Regression Analysis

In general, multiple regression is a statistical technique through which the relationship between a dependent variable and a set of independent variables can be analyzed.²⁸ After the velocities in the previous section are found a multiple regression analysis is performed using the properties of soils and leachates (independent variables) from the laboratory column

Table 1
CADMIUM RELATIVE CONCENTRATION c/c_0 FOR ANTHONY s I PERFUSED
WITH LEACHATE CONTAINING 1600 ppm SALTS AND 2600 ppm TOC

Depth	Time (days)									
(cm)	0.1	2.0	4.0	6.0	8.0	10.0	15.0	20.0	25.0	30.0
2.0	0.32608	0.92143	0.99239	0.99927	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
4.0	0.07413	0.76242	0.96273	0.99502	0.99943	1.00000	1.00000	1.00000	1.00000	1.00000
6.0	0.00000	0.56976	0.89900	0.98187	0.99713	1.00000	1.00000	1.00000	1.00000	1.00000
8.0	0.00000	0.38929	0.80001	0.95326	0.99100	0.99845	1.00000	1.00000	1.00000	1.00000
10.0	0.00000	0.24614	0.67538	0.90389	0.97746	0.99546	1.00000	1.00000	1.00000	1.00000
12.0	0.00000	0.14549	0.54060	0.83203	0.95271	0.98886	0.99982	1.00000	1.00000	1.00000
14.0	0.00000	0.08106	0.41100	0.74047	0.91344	0.97634	0.99947	1.00000	1.00000	1.00000
16.0	0.00000	0.04286	0.29761	0.63569	0.85801	0.95531	0.99866	1.00000	1.00000	1.00000
18.0	0.00000	0.02161	0.20592	0.52605	0.78696	0.92348	0.99696	1.00000	1.00000	1.00000
20.0	0.00000	0.01044	0.13657	0.41972	0.70313	0.87928	0.99374	1.00000	1.00000	1.00000
22.0	0.00000	0.00000	0.8709	0.32317	0.61118	0.82235	0.98815	0.99960	1.00000	1.00000
24.0	0.00000	0.00000	0.05354	0.24045	0.51643	0.75399	0.97908	0.99915	1.00000	1.00000
26.0	0.00000	0.00000	0.03181	0.17313	0.42411	0.67676	0.96518	0.99832	1.00000	1.00000
28.0	0.00000	0.00000	0.01831	0.12082	0.33865	0.59393	0.94503	0.99682	1.00000	1.00000
30.0	0.00000	0.00000	0.01023	0.08186	0.26313	0.50918	0.91755	0.99425	1.00000	1.00000
32.0	0.00000	0.00000	0.00000	0.05392	0.19905	0.42641	0.88228	0.99004	0.99960	1.00000
34.0	0.00000	0.00000	0.00000	0.03457	0.14670	0.34903	0.83930	0.98345	0.99916	1.00000
36.0	0.00000	0.00000	0.00000	0.02161	0.10546	0.27932	0.78889	0.97364	0.99839	1.00000
38.0	0.00000	0.00000	0.00000	0.01319	0.07404	0.21851	0.73142	0.95990	0.99709	1.00000
40.0	0.00000	0.00000	0.00000	0.00000	0.05080	0.16710	0.66774	0.94175	0.99496	1.00000
42.0	0.00000	0.00000	0.00000	0.00000	0.03408	0.12504	0.59962	0.91895	0.99161	1.00000
44.0	0.00000	0.00000	0.00000	0.00000	0.02238	0.09169	0.52971	0.89127	0.98661	0.99891
46.0	0.00000	0.00000	0.00000	0.00000	0.01441	0.06595	0.46084	0.85827	0.97954	0.99820
48.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.04653	0.39521	0.81929	0.97008	0.99708
50.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.03219	0.33404	0.77378	0.95804	0.99535
52.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.02184	0.27790	0.72179	0.94325	0.99278
54.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.01456	0.22714	0.66442	0.92541	0.98913
56.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.18221	0.60372	0.90398	0.98420
58.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.14356	0.54222	0.87806	0.97786
60.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.11131	0.48217	0.84663	0.97000
64.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.06443	0.37138	0.76470	0.94914
68.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.03558	0.27402	0.66062	0.91845
72.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.01848	0.18997	0.54881	0.87102
76.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.12287	0.44458	0.80004
80.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.07548	0.35287	0.70652
84.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.04518	0.27035	0.60212
88.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.02643	0.19535	0.50207
92.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.01477	0.13157	0.41470
96.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.08347	0.33831
100.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.05137	0.26733

From Amoozegar-Fard, A., Fuller, W. H., and Warrick, A. W., *J. Environ. Qual.*, 13, 290, 1984.

experiments. A stepwise inclusion approach is employed in the regression analysis in which the independent variables are entered into the equation one by one. In stepwise inclusion, the variable that explains the greatest amount of variance in the dependent variable enters the equation first. The variable that explains the greatest amount of variance not explained by the variable(s) already in the equation enters the equation in subsequent steps. For more information on multiple regression, see Kim and Kohout.²⁸

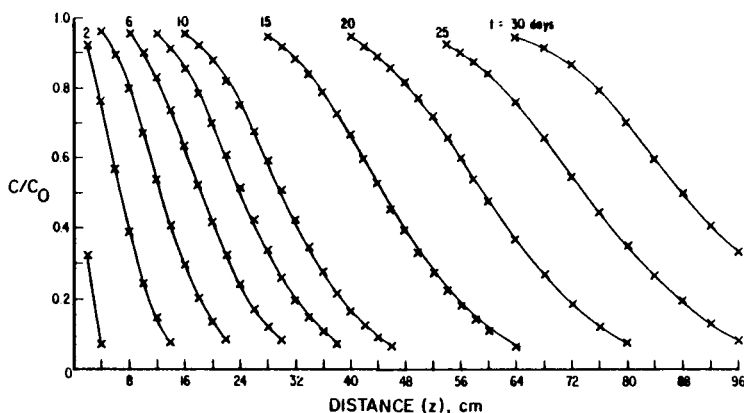


FIGURE 1. Calculated values and fitted curves for distance vs. c/c_0 for $t = 0.1$ through 30 days. (From Amoozegar-Fard, A., Fuller, W. H., and Warrick, A. W., *J. Environ. Qual.*, 13, 290, 1984. With permission.)

Table 2
THE DEPTH z FOR RELATIVE CONCENTRATION $c/c_0 = 0.1, 0.2, \dots, 0.9$ AT VARIOUS TIMES

Time (days)	c/c_0								
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
2.0	13.28	10.83	9.17	7.87	6.73	5.69	4.68	3.56	2.28
4.0	21.41	18.15	15.95	14.18	12.61	11.11	9.64	8.00	5.98
6.0	28.99	25.15	22.52	20.39	18.48	16.65	14.80	12.73	10.14
8.0	36.31	31.97	28.99	26.54	24.35	22.24	20.07	17.66	14.56
10.0	43.45	38.68	35.38	32.66	30.22	27.86	25.42	22.69	19.15
15.0	60.83	55.17	51.19	47.85	44.85	41.99	39.01	35.58	31.05
20.0	77.69	71.48	66.88	62.91	59.40	56.12	52.78	48.88	43.41
25.0	94.39	87.73	82.52	77.88	73.82	70.16	66.56	62.43	56.33
30.0	100.00	100.00	98.14	92.74	88.09	84.08	80.26	76.00	69.78

2. Soil and Leachate Properties in the Regression Analysis

The soil and leachate properties introduced into the regression analysis are given in Table 3. Clay, silt, sand and FeO content of the soil describe most of the variation. Soil properties such as CEC, EC of the extract, Mn content, surface area, bulk density and particle density are largely accounted for indirectly and increase the fit only marginally for cases seen.²³

Readily measureable leachate properties that affect pollutant migration the most are, concentration of total organic carbon components, and common inorganic salts determined either individually, as Ca, Mg, Na, K, Cl, SO_4 , or collectively as measured by the electrical conductivity (EC), and finally the pH. The relationship of these factors in the attenuation of metals by soils are discussed more fully in Chapter 1, Volume I, and Chapter 4, Volume II. For the most part, attenuation is compared under conditions of relatively constant pH values. Maximum decrease of metals takes place near the neutral range (6.8 to 7.2). Minimum attenuation occurs in the acid pH ranges and the maximum in the moderate alkaline pH levels. The leachates used in the development of the equations reported here represent young (i.e., less than 3.5 years old) and acid (pH 5.4 to 6.2) fluids. Therefore, the predictions of metal migrations also represent minimum attenuation and maximum migrations.

3. Predictive Equations

Two separate regression analyses are performed for developing predictive equations for

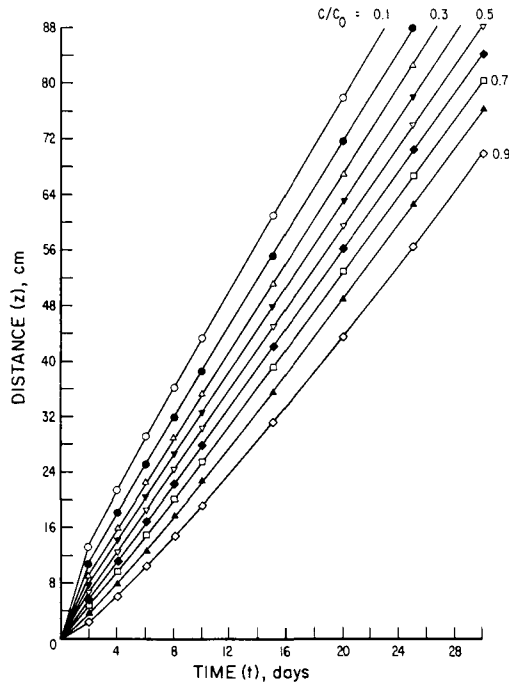


FIGURE 2. Calculated values of distance vs. time for c/c_0 , = 0.1, 0.2, . . . , 0.9. (From Amoozegar-Fard, A., Fuller, W. H., and Warrick, A. W., *J. Environ. Qual.*, 13, 290, 1984. With permission.)

Cd, Ni, and Zn.²⁹⁻³¹ Table 4 shows the number of cases used in an example regression analysis. In the single enrichment, only one element (Cd, Ni or Zn) is added to the leachate before it is perfused through the column. In the multiple enrichment, however, the three elements are present in different combinations as shown in Table 4.⁷

Given in Table 5 are the regression equations which have been developed to predict the velocity of each relative concentration for single and combined enrichments for the three elements Cd, Ni and Zn. V_i is the velocity of relative concentration $c/c_0 = i$, ($i = 0.1, 0.2, \dots, 0.9$) and v is the pore water velocity. The units for v are L/T (i.e., length over time such as cm/d or mm/h). The dimensions for V_i 's are the same as v .

IV. ERROR FUNCTION MODEL

The usual sigmoid shape of the breakthrough curves describing the movement of ions in solution through soil lends itself to general empirical approximations. Alternative models, to that of the Lapidus-Amundson, therefore, are possible that may be simpler which work just as well for some applications. One such model is the Error Function model, which is now introduced.

A. Solute Profile

For a non-reactive solute such as Cl, the position and the shape of the solute profile depends on the pore-water velocity and apparent diffusion coefficient. Figures 3A to D present the profile for a pulse of a non-reactive solute for four different cases (water with no solute is applied to the soil followed by a known quantity of solute with concentration c_0 which again is followed by water with no solute). Note that the area under all four curves

Table 3
SOIL AND LEACHATE
PROPERTIES USED IN
REGRESSION ANALYSIS

Soil	Leachate
Clay (%)	Common salts (ppm)
Silt (%)	(Ca, Mg, Na, and K)
Sand (%)	Total organic carbon (ppm)
FeO (%)	(TOC)

Table 4
NUMBER OF CASES FOR EXPERIMENTAL
STUDY, PARAMETER ESTIMATION, AND
CALCULATION OF VELOCITIES FOR c/c_0

		Experiment element	No. of cases for experiment	Parameters estimated	Velocities calculated
Single Enrichment					
		Cd	84	75	75
		Ni	38	44	44
		Zn	49	44	29
Multiple Enrichment					
	Cd	Cd	14	13	11
+					
	Ni	Ni	14	14	13
	Cd	Cd	14	14	11
+					
	Zn	Ni	14	13	13
	Cd	Cd	15	15	14
+					
	Ni	Ni	15	15	15
+					
	Zn	Zn	15	13	13

From Fuller, W. H., Amoozegar-Fard, A., Niebla, E., and Boyle, M., Land Disposal: Hazardous Wastes, Schultz, D., Ed., Proc. 7th Annu. Res. Symp., U.S. EPA-600/9-81-0026, U.S. Environmental Protection Agency, 1981, 18.

Table 5
REGRESSION EQUATIONS DESCRIBING THE VELOCITY OF Cd, Ni, AND Zn
OBTAINED FOR SINGLE AND MULTIPLE ENRICHMENTS OF MUNICIPAL
SOLID WASTE LANDFILL LEACHATES USING THE L-A MODEL

- A. The equations describing the velocity of Cd obtained from single enrichment
- B. The equations describing the velocity of Cd obtained from single and multiple enrichments
- C. The equations describing the velocity of Ni obtained from single enrichment
- D. The equation describing the velocity of Ni obtained from single and multiple enrichment
- E. The equations describing the velocity of Zn obtained from single enrichment
- F. The equations describing the Zn velocity obtained from single and multiple enrichments

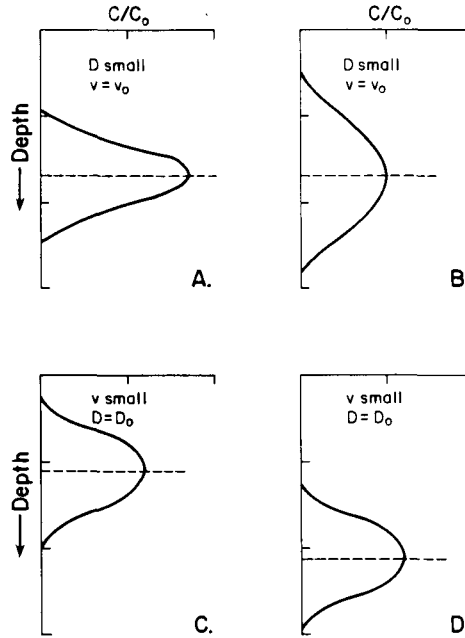


FIGURE 3. Effect of diffusion coefficient D (parts A and B) and pore water velocity v (parts C and D) on the solute profile.

is the same. Keeping the apparent diffusion coefficient constant, the position of the solute profile depends on the pore-water velocity. The greater the pore-water velocity, the deeper is the solute profile (Figures 3 A and B). Because D is the same, the shape of the profile is the same. Figures 3 C and D are for constant flux, different diffusion coefficients. The location of the center of the profile is at the same depth, however, for large values of D , the solute profile is spread over a larger distance and the maximum concentration is less than the case where D is small. The same is true for a step input (i.e., water with no solute is followed by water with solute concentration c_0). The results for step input are presented in Figures 3 A-D.

For a reactive solute the adsorption-desorption, precipitation and any other reactions all tend to retain and attenuate the breakthrough of the material. The retention within the soil profile affects the location and the shape of the solute front. The approach with the Error Function Model is to fit the general shape of the breakthrough results. Therefore, the solute profile for a reactive salt can be described with the same type of results, developed for a non-reactive solute, provided that the pore-water velocity and apparent diffusion coefficient are generalized.

B. Defining the Model

The error function model for a one dimensional flow for a step input of salt results in a sigmoidal breakthrough curve

$$c/c_0 = 0.5 \operatorname{erfc} [(Rz - vt)/(4DRt)^{0.5}] \quad (9)$$

and has been used extensively for miscible displacement studies. In the above equation, c is the concentration of soil water; c_0 , concentration of input solution; z , depth; t , time; v , pore water velocity; R , retardation factor (dimensionless); D , diffusion-dispersion coefficient (dimensions L^2/T); and erfc the complementary error function defined by

$$\operatorname{erfc}(x) = (2/\pi^{0.5}) \int_x^\infty \exp(-\beta^2) d\beta \quad (10)$$

(See Abramowitz and Stegun, 1970). Using experimental data, the parameters R and D can be estimated by any suitable minimization technique.

Because of the simplicity of Equation 9, the two parameters R and D can be estimated explicitly and most easily as follows.³¹ With time t in terms of pore volume P , length of interest L , and pore water velocity v

$$t = PL/v \quad (11)$$

Equation 9 yields

$$(RLv/4DP)^{0.5} - (LvP/4DR)^{0.5} = \operatorname{erfc}^{-1}(2c/c_o) \quad (12)$$

in which $\operatorname{erfc}^{-1}(2c/c_o)$ is the inverse complementary error function of $2c/c_o$. Assume that c_i/c_o and P_i are the measured values of the relative concentration and pore volume displacement for the i th point, and n is the total number of experimental points. Minimization of the sum of the squares of the differences between calculated $\operatorname{erfc}^{-1}(2c/c_o)$ and experimental values of $\operatorname{erfc}^{-1}(2c_i/c_o)$ results in explicit relationships for R and D :

$$R = a/b \quad (13)$$

$$D = Lv/(4ab) \quad (14)$$

with

$$a = \frac{n \sum [P_i^{0.5} \operatorname{erfc}^{-1}(2c_i/c_o)] - \sum P_i \sum [\operatorname{erfc}^{-1}(2c_i/c_o)/P_i^{0.5}]}{n^2 - \sum P_i \sum (1/P_i)} \quad (15)$$

and

$$b = (a/n) \sum (1/P_i) - (1/n) \sum [\operatorname{erfc}^{-1}(2c_i/c_o)/P_i^{0.5}] \quad (16)$$

where the sums are taken over the n points.

These expressions are easily found with a small calculator. Table 6 presents the values of $\operatorname{erfc}^{-1}(2c_i/c_o)$ for 19 values of c_i/c_o from 0.05 to 0.95. If necessary, other values can be calculated by interpolation. Table 6 is useful to find $\operatorname{erfc}^{-1}(2c_i/c_o)$ for the n experimental values. Substitution of corresponding values of P_i and $\operatorname{erfc}^{-1}(2c_i/c_o)$ in Equation 15 gives a . Use of Equation 15 and the calculated value of a with corresponding values of P_i and $\operatorname{erfc}^{-1}(2c_i/c_o)$ gives b from which R and D are defined.

Due to the nature of Equation 10, and because the parameter estimation technique uses the inverse of the complementary error function, the best results are obtained when the experimental points are chosen between values of $c/c_o = 0.05$ and 0.95 . Comparison with the experimental results that are collected at extreme ends of a breakthrough curve is therefore inadvisable. In such cases, a smoothed curve can be constructed between the data points and comparison should be made with the smoothed curve.

C. Regressing A and D_e to Soils and Leachates Properties

A multiple regression analysis was performed to regress the factors $A = v/R$ and $D_e = DR$ to soils and leachate properties. Factor A was selected because it is equivalent to the

Table 6
REGRESSION EQUATIONS DESCRIBING THE VELOCITY OF Cd, Ni, AND Zn
OBTAINED FOR SINGLE AND MULTIPLE ENRICHMENTS OF MUNICIPAL
SOLID WASTE LANDFILL LEACHATES USING THE ERROR FUNCTION AND
FACTOR A

Cadmium: single enrichment (75 cases)

$$A = 1.24644/\text{CLAY} + (0.45812 \times 10^{-4}) \times (\text{CLAY} + \text{SILT})^2 \\ + 0.39219/\text{FeO} + (0.46542 \times 10^{-3}) \times \text{FeO}^2 \\ + 3.33632 \times \text{SALTS} - 7.89111 \times \text{SALTS}^2 \\ + (0.18812 \times 10^{-1}) \times \text{TOC} - 0.53462 \\ r^2 = 0.844$$

Cadmium: single enrichment + multiple enrichment (114 cases)

$$A = 1.320812/\text{CLAY} + (0.102222 \times 10^{-1}) \times \text{CLAY} \\ - 4.165096/\text{SILT} + (0.5105996 \times 10^{-1}) \times \text{SAND} \\ + (0.3958611 \times 10^{-3}) \times (\text{CLAY} + \text{SILT})^2 + 3.758737 \times \text{SALTS} \\ - 9.027812 \times \text{SALTS}^2 + (0.292821 \times 10^{-1}) \times \text{TOC} - 4.060716 \\ r^2 = 0.789$$

Nickel: single enrichment (44 cases)

$$A = 0.774228/\text{CLAY} + 1.111404/\text{SAND} \\ + 0.277297/\text{FeO} + (0.132569 \times 10^{-1}) \times \text{FeO} \\ + 2.946547 \times \text{SALTS} - 9.426479 \times \text{SALTS}^2 \\ - 1.367580 \times \text{TOC} + 4.852866 \times \text{TOC}^2 - 0.269209 \\ r^2 = 0.922$$

Nickel: single enrichment + multiple enrichment (72 cases)

$$A = (0.7706279 \times 10^{-1}) \times \text{CLAY} - (0.8759624 \times 10^{-3}) \times \text{CLAY}^2 \\ + 8.400334/\text{CLAY} - 4.996407/\text{SILT} \\ + (0.1439113 \times 10^{-3}) \times \text{SAND}^2 - 0.541805/\text{FeO} \\ r^2 = 0.857$$

Zinc: single enrichment (29 cases)

$$A = (0.8169938 \times 10^{-3}) \times \text{SAND} + (0.2616558 \times 10^{-4}) \times \text{SILT}^2 \\ + 0.103803/\text{FeO} + (0.164495 \times 10^{-3}) \times \text{FeO}^2 \\ - 0.558264 \times \text{TOC} + 2.950986 \times \text{TOC}^2 + 2.132009 \times \text{SALTS} \\ - 5.705847 \times \text{SALTS}^2 - 0.217165 \\ r^2 = 0.852$$

Zinc: single enrichment + multiple enrichment (54 cases)

$$A = 0.58585/\text{CLAY} + (0.49088 \times 10^{-3}) \times \text{CLAY}^2 \\ - 1.19753/\text{SILT} - 0.75659/\text{SAND} \\ + (0.10297 \times 10^{-1}) \times \text{SAND} + (0.12923 \times 10^{-3}) \times \text{SAND}^2 \\ + 0.14156 \times \text{SALTS} + (0.51133 \times 10^{-1}) \times \text{TOC} + 0.16402 \\ r^2 = 0.691$$

Chromium: single enrichment (36 cases)

$$A = - (0.114364 \times 10^{-1}) \times \text{SAND} + 2.11050/\text{SAND} \\ + (0.796678 \times 10^{-1}) \times (\text{SAND} \times \text{TOC}) \\ + (0.594647 \times 10^{-1}) \times (\text{SAND} \times \text{SALTS}) \\ + (0.186388 \times 10^{-1}) \times (\text{SILT} \times \text{SALTS}) - 0.32415 \times \text{SALTS} - 0.21340 \\ r^2 = 0.737$$

velocity of the relative concentration $c/c_o = 0.5$ (i.e., $(\partial z/\partial t) = A$). Factor D_e , a modified apparent diffusion coefficient, results from dividing numerator and denominator of Equation 9 by R .

1. Factor A

For Cd, Ni, and Zn a hierarchical inclusion procedure²⁸ was used in which the factors that appear in the corresponding equation for velocity of $c/c_o = 0.5$ obtained through the Lapidus-Amundson model were entered into the equation one by one. For Cr^{+6} , however, a stepwise inclusion (as described earlier) was used.

The resulting equations for Cd, Ni, and Zn, both for single enrichment and single + multiple enrichment cases with the corresponding r^2 , follow in Table 7. Included are the number of cases on which the coefficients were fitted.

2. Factor D_e

A stepwise inclusion procedure was used and the modified diffusion coefficients, D_e , for Cd, Ni, Zn, and Cr were regressed against the soil and leachate properties. The predictive equations for Cd, Ni, and Cr appear in Table 8. Although the parameters entering the regression equations for D_e for Zn as single enrichment and single + multiple enrichments were significantly (at 1% level) important, the overall r^2 value did not exceed 0.6 for single enrichment and 0.3 for single + multiple enrichments. Therefore, these two equations are not presented.

V. APPLICATION OF PREDICTIVE EQUATIONS

In this section the procedure for calculating the velocity of a relative concentration for a particular element, through soil, using the Lapidus-Amundson model is presented.²³ The application of the error function model also is discussed.³¹

A. Example Using L-A Model

Let us assume that the soil under a landfill or waste disposal pond has the following characteristics:

- Clay content = 30%
- Silt content = 59%
- Water (leachate) filled porosity = $0.07 \text{ cm}^3/\text{cm}^3$
- Free iron oxide = 4.0%

Suppose the leachate has:

- Total soluble salts (Ca + Mg + Na + K) = 0.11% (1100 ppm)
- Total organic carbon = 0.21% (2100 ppm)
- Cadmium concentration = 4.0 ppm

Furthermore let's assume that:

- Infiltration rate into the soil (Darcian velocity) = 0.1 cm/d
- Depth to ground water = 5 m

The question is: How long will it take for the soil solution having a concentration of 1.2 ppm of cadmium to reach the ground water, if the flow of contaminated leachate into the soil is continuous?

The pore water velocity is

Table 7
REGRESSION EQUATIONS DESCRIBING THE VELOCITY OF Cd, Ni, AND Zn
OBTAINED FOR SINGLE AND MULTIPLE ENRICHMENTS OF MUNICIPAL
SOLID WASTE LANDFILL LEACHATES USING THE ERROR FUNCTION AND
THE MODIFIED DIFFUSION COEFFICIENTS, D_e

Cadmium: single enrichment (75 cases)

$$D_e = 117.51975/\text{CLAY} + (0.21814 \times 10^{-2}) \times \text{CLAY}^2 \\ + (0.23083 \times 10^{-2}) \times \text{SAND}^2 - 140.99631/\text{SILT} \\ - 5.14458/\text{FeO} + 21.00761 \times \text{SALTS} - 48.70701 \times \text{SALTS}^2 \\ + 0.802353 \times \text{TOC} - 2.72247 \\ r^2 = 0.672$$

Cadmium: single + multiple enrichments (114 cases)

$$D_e = 106.50939/\text{CLAY} + (0.16731 \times 10^{-2}) \times \text{CLAY}^2 \\ + (0.27612 \times 10^{-2}) \times \text{SAND}^2 - 157.89397/\text{SILT} \\ - 5.29039/\text{FeO} - (0.69839 \times 10^{-2}) \times (\text{SAND} \times \text{SILT}) \\ + 12.43084 \times \text{SALTS} - 1.06684 \times \text{TOC}^2 + 2.99291 \\ r^2 = 0.658$$

Nickel: single enrichment (44 cases)

$$D_e = -0.32446 \times \text{SAND} + 114.17017/\text{SILT} + 21.7008/\text{FeO} \\ + (0.25994 \times 10^{-1}) \times (\text{SILT} \times \text{FeO}) - 1.84449 \times (\text{CLAY} \times \text{TOC}) \\ - 1.48796 \times (\text{SILT} \times \text{TOC}) + 523.2265 \times \text{TOC}^2 \\ + 13.53508 \times \text{SALTS} - 1.88937 \\ r^2 = 0.834$$

Nickel: single + multiple enrichments (72 cases)

$$D_e = -1.45958 \times \text{CLAY} + (0.21765 \times 10^{-1}) \times \text{CLAY}^2 \\ + 1.66914 \times \text{SAND} - 175.87125/\text{SAND} - 102.58816/\text{SILT} \\ + (0.16425 \times 10^{-1}) \times (\text{CLAY} + \text{SILT})^2 + 20.26271 \times \text{SALTS} \\ - 4.26259 \times \text{TOC}^2 - 105.86194 \\ r^2 = 0.645$$

Chromium (36 cases)

$$D_e = 111.2768/\text{CLAY} + (0.774612 \times 10^{-2}) \times \text{CLAY}^2 \\ - 642.9528/\text{SILT} - 0.83472 \times \text{SAND} \\ - 5.8010 \times (\text{CLAY} \times \text{TOC}) + 10.3583 \times (\text{SAND} \times \text{TOC}) \\ + 207.9245 \times \text{SALTS} - 40.5391 \times \text{SALTS}^2 + 3.7450 \\ r^2 = 0.713$$

$$v = \frac{\text{Infiltration rate}}{\text{Water filled porosity of soil}} = \frac{0.1}{0.07} = 1.43 \text{ cm/d}$$

The relative concentration of interest $c/c_o = 1.2/4.0 = 0.3$.

Substitution of the appropriate values into the L-A model equation for V_3 for cadmium (Table 5) results in

$$V_3 = \frac{1.43}{25} [30.6526/30 + 0.0011155 \times 70^2 + 9.0574/4.0 \\ + 0.010611 \times 4.0^2 + 87.318 \times 0.11 - 212.2545 \times 0.11^2 \\ + 0.3388 \times 0.21 - 13.0778] = 0.362 \text{ cm/d}$$

Table 8
RELATIVE
CONCENTRATION c/c_0
AND CORRESPONDING
VALUES OF INVERSE
COMPLEMENTARY
ERROR FUNCTION OF
 $2c/c_0$

c/c_0	$\text{erfc}^{-1}(2c/c_0)$
0.05	1.1610
0.1	0.9062
0.15	0.7329
0.2	0.5951
0.25	0.4770
0.3	0.3708
0.35	0.2725
0.4	0.1791
0.45	0.0889
0.5	0.00
0.55	-0.0889
0.6	-0.1791
0.65	-0.2725
0.7	-0.3708
0.75	-0.4770
0.8	-0.5951
0.85	-0.7329
0.9	-0.9062
0.95	-1.1610

From Amoozegar-Fard, A., Warrick,
A. W., and Fuller, W. H., *Soil Sci.*
Soc. Am. J., 47, 1047, 1984.

For the ground water at 5 m then, it would take approximately 3.78 years before the relative concentration 0.3 (i.e., soil solution with concentration of 1.2 ppm) reaches the water table. Using the alternative equation for single + multiple enrichment, the velocity would be 0.33 cm/d giving 4.15 years, a reasonably close agreement.

B. Example Using E-F Model

The predictive equations from the Error Function model as well as L-A model can be used to construct a breakthrough curve for the metal under consideration at any depth. Using the breakthrough, the time necessary for the soil solution with a known concentration to reach the water table or a given depth can be calculated. The model can also be used to determine the solute profile at a given time. The parameter R and D in the error function model can be obtained from the appropriate table or may be directly estimated from experimental data.

As an example, the Error Function solution is best fitted to 11 points for the movement of Cr (VI), present in landfill type leachate, through a column of Ava silty clay loam soil see Figure 4. The leachate contained 980 mg L⁻¹ of total organic carbon and 590 mg L⁻¹ of soluble salts. The values for R and D were 7.3 (dimensionless) and 8.3 cm² d⁻¹, respectively.³¹

The estimated values of the retardation factor R and apparent diffusion coefficient D , i.e., 7.3 (dimensionless) and 8.3 cm² d⁻¹, respectively, were used to calculate the Cr profile

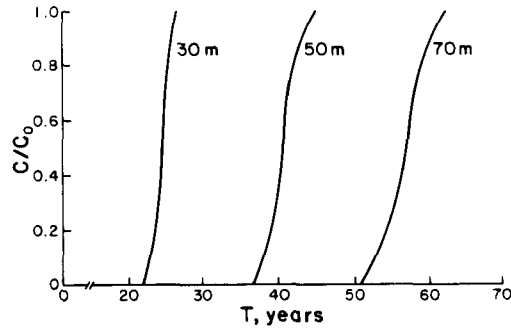


FIGURE 4. Cadmium breakthrough curves at 30, 50, and 70 m of soil depth calculated from equations from single enrichment obtained by the Lapidus-Amundson model. (From Amoozegar-Fard, A., Fuller, W. H., and Warrick, A. W., *J. Environ. Qual.*, 13, 290, 1984. With permission.)

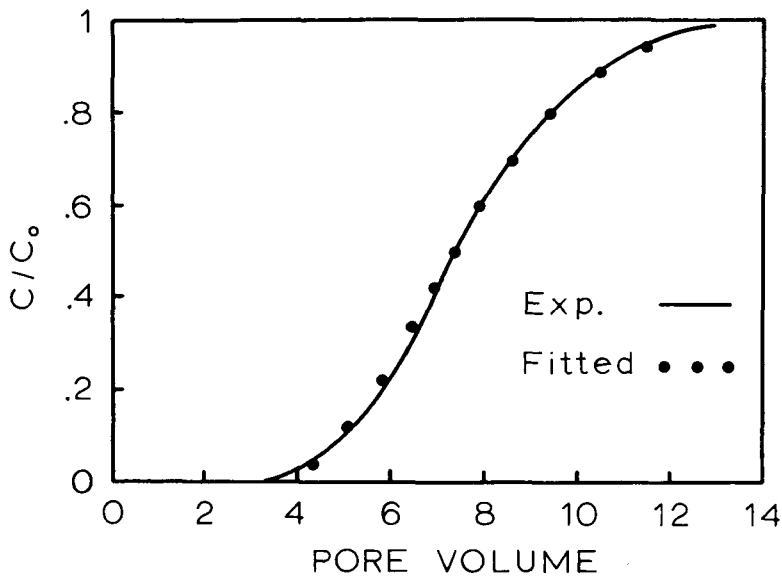


FIGURE 5. Chromium breakthrough for Ava silty clay loam. (From Amoozegar-Fard, A., Warrick, A. W., and Fuller, W. H., *Soil Sci. Soc. Am. J.*, 47, 1047, 1983. With permission.)

after 150, 200 and 250 days for an Ava silty clay loam soil with pore water velocity of 18 cm d^{-1} (Figure 5). The sensitivity of the results with respect to variation of R , D , and v were tested by:

- (a) varying R by 20% (e.g., $R = 6.1$, $R = 7.3$, $R = 8.8$) while keeping D and v constant.
- (b) keeping R and v constant and using $D = 0$ and 16.6 rather than $8.3 \text{ cm}^2 \text{ d}^{-1}$.
- (c) keeping R and D constant and varying v by 20% (e.g., $v = 15$, 18 and 21.6 cm d^{-1}).

The resulting profiles after 200 days for all analyses are presented in Figures 5 B, C, and D, respectively.

The results indicate that the solute front is less sensitive to variation in D compared to

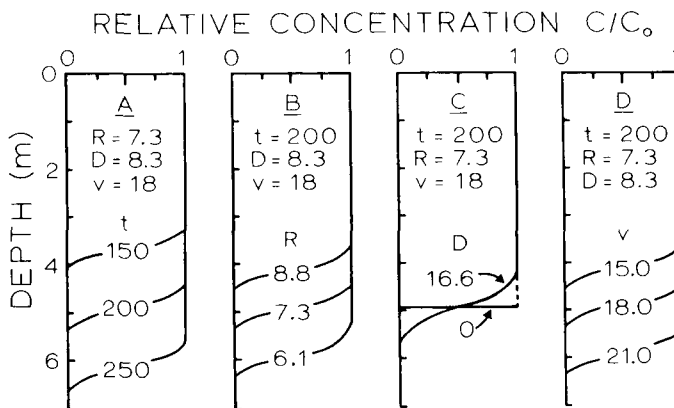


FIGURE 6. Chromium profiles calculated with the Error Function Model.
(From Amoozegar-Fard, A., Warrick, A. W., and Fuller, W. H., *Soil Sci. Soc. Am. J.*, 47, 1047, 1983. With permission.)

variation in R or v (see Figures 6 B, C, and D). Assuming no diffusion (i.e., $D = 0$) results in a sharp front that can be calculated from the estimated value of R and known value of pore water velocity v .

C. Interpretation of Results

The equations presented under Development and Prediction aid in determining the time that the soil water with a given concentration reaches a certain depth; or they can be used to calculate what the concentration of soil water is at a given time and depth above the water table if the concentration of leachate entering the profile is known. Nothing can be said about the level of pollutants in the ground water unless the complex hydrological aspects of the system are fully known. Depending on the size of the aquifer and the rate of underground water flow, the concentration of a hazardous element in water may or may not reach a dangerous level in a short time even though the concentration of that element in the leachate might seem low. On the other hand, if the ground water aquifer is large and the horizontal movement of water is appreciable, the level of contaminants might not reach an alarming level for a long period of time, if ever. Therefore, the users of the equations must be aware of the limitations which are the results of the experimental and theoretical conditions of the procedures used in their development. In addition, they must consider physical, chemical and hydrological aspects of the waste disposal system before drawing a conclusion with respect to ground water contamination.

Special caution should be exercised when extrapolating beyond the time frame and spatial configurations on which the original data was collected. More comprehensive models are available for predictive purposes. However, due to the complicated nature of such models, practical application is often difficult. The present model is simple to apply and results in a more objective procedure for predictions than those based only on personal judgment.

REFERENCES

1. Lapidus, L. and Amundson, N. R., Mathematics of absorption in beds. VI. The effect of longitudinal diffusion in ion exchange and chromatographic columns, *J. Phys. Chem.*, 56, 984, 1952.
2. Fuller, W. H., Movement of Selected Metals, Asbestos and Cyanide in Soil: Application to Waste Disposal, U.S. EPA-600/2-77-020, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1977, 243.

3. **Fuller, W. H.**, Investigation of Landfill Leachate Pollutant Attenuation by Soils, U.S. EPA-600/2-78-158, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1978, 219.
4. **Amoozegar-Fard, A., Warrick, A. W., and Fuller, W. H.**, Movement of selected organic solvents through soils, 1983. (Submitted to *Soil Science Soc. Am. J.* for publication).
5. **Fuller, W. H.**, Soil and leachate parameters affecting heavy metal transport, EOS, *Trans. Am. Geophys. Union*, 60, 256, 1979.
6. **Fuller, W. H.**, Management of saline soils, *Outlook Agric.*, 10, 13, 1979.
7. **Fuller, W. H., Amoozegar-Fard, A., Niebla, E., and Boyle, M.**, Behavior of Cd, Ni, and Zn in single and mixed combinations in landfill leachates, in *Land Disposal: Hazardous Wastes*, Shultz, D., Ed., Proc. 7th Annu. Res. Symp., U.S. EPA-600/9-81-0026, U.S. Environmental Protection Agency, MERL, 1981, 18.
8. **Fuller, W. H.**, Methods for conducting soil column tests to predict pollutant movement, in *Land Disposal: Hazardous Wastes*, Shultz, D., Ed., Proc. Eighth Ann. Res. Symp., U.S. EPA-600/9-82-002, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1982, 87.
9. **Fuller, W. H.**, Soil-waste interactions, in *Disposal of Industrial and Oily Sludges by Land Cultivation*, Resource Systems Management Association, Northfield, N.J., 1980, 79.
10. **Fuller, W. H.**, Soil modification to minimize movement of pollutants from solid waste operation, *Critical Review, Environmental Control*, CRC Press, Boca Raton, Fla., 9, 213, 1980.
11. **Maisel, H. and Gnugnoli, G.**, Simulation of Discrete Stochastic Systems, Sci. Res. Assoc., Inc., Chicago, Ill., 1972, 465.
12. **Van Genuchten, M. T.**, Simulation models and their application to landfill disposal siting: a review of current technology, in *Land Disposal: Hazardous Wastes*, Shultz, D., Ed., Proc. Fourth Ann. Res. Symp., U.S. EPA-600/9-78-016, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1978, 425.
13. **Van Genuchten, M. T.**, Analytical solutions for chemical transport with simultaneous adsorption, zero-order production and first-order decay, *J. Hydrology*, 49, 213, 1981.
14. **Biggar, J. W. and Nielsen, D. R.**, Miscible displacement and leaching phenomenon, in *Irrigation of Agricultural Lands*, Hagan, R. M., Haise, H. R., and Edminister, T. W., Eds., *Agronomy*, 11, 254, 1967.
15. **Warrick, A. W., Biggar, J. W., and Nielsen, D. R.**, Simultaneous solute and waste transfer for an unsaturated soil, *Water Resour. Res.*, 7, 1216, 1971.
16. **Sposito, G.**, On the use of the Langmuir equation in the interpretation of "Adsorption phenomena: II. The 'Two-Surface' Langmuir equation, *Soil Sci. Soc. Amer. J.*, 46, 1147, 1982.
17. **Bresler, E.**, Anion exclusion and coupling effects on nonsteady transport through unsaturated soils: I. Theory, *Soil Sci. Am. Proc.*, 37, 663, 1973.
18. **Bresler, E. and Laufer, A.**, Anion exclusion and coupling effects on nonsteady transport through unsaturated soils. II. Laboratory and numerical experiments, *Soil Sci. Soc. Am. Proc.*, 38, 213, 1974.
19. **Skopp, J. and Warrick, A. W.**, A two-phase model for the miscible displacement of reactive solutes in soils, *Soil Sci. Soc. Am. Proc.*, 38, 545, 1974.
20. **Van Genuchten, M. T. and Wienenga, P. J.**, Mass transfer studies in sorbing porous media: I. Analytical solution, *Soil Sci. Soc. Am. J.*, 40, 473, 1976.
21. **Melamed, D., Hanks, R. J., and Willardson, L. S.**, Model of salt flow in soil with a source-sink term, *Soil Sci. Soc. Am. J.*, 41, 29, 1977.
22. **Amoozegar-Fard, A., Nielsen, D. R., and Warrick, A. W.**, Soil solute concentration distribution for spatially varying pore water velocities and apparent diffusion coefficients, *Soil Sci. Soc. Am. J.*, 46, 3, 1982.
23. **Amoozegar-Fard, A., Fuller, W. H., and Warrick, A. W.**, An approach to predicting the movement of selected polluting metals in soil, *J. Environ. Qual.*, 13, 290, 1984.
24. **Warrick, A. W. and Nielsen, D. R.**, Spatial variability of soil physical properties in the field, in *Application of Soil Physics*, Hillel, D., Ed., Academic Press, New York, 1980, 319.
25. **Davidon, W. D.**, Variable metric method of mineralization, ANL-5990, U.S. Atomic Energy Research and Development Rep., Argonne Natl. Lab., Chicago, Ill., 1959.
26. **Abramowitz, M. and Stegun, I. A.**, *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables*, U.S. Department of Commerce, Nat'l. Bur. Std: Applied Math. Ser. 1970, 55.
27. **Erh, K. T.**, Application of the spline function to soil science, *Soil Sci.*, 114, 333, 1972.
28. **Kim, J. and Kohout, F. J.**, Multiple regression analysis: subprogram regression, in *Statistical Package of Social Sciences (SPSS)*, 2nd Ed., Nie, N. H., Hull, C. H., Jenkins, J. G., Steinbrenner, K., and Bent, D. H., Eds., 2nd Ed., McGraw-Hill Book Co., New York, 1975, chap. 3.
29. **Lomen, D. O., Tonnellato, P. J., and Warrick, A. W.**, Salt and water transport in unsaturated soil for nonconservative systems, *Agric. Water Manage.*, 8, 397, 1984.
30. **Skopp, J., Gardner, W. R., and Tyler, E. J.**, Solute movement in structured soils: two-region model with small interaction, *Soil Sci. Soc. Am. J.*, 45, 837, 1981.
31. **Amoozegar-Fard, A., Warrick, A. W., and Fuller, W. H.**, A simplified model for solute movement through soils, *Soil Sci. Soc. Am. J.*, 47, 1047, 1983.



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

Chapter 6

EFFECT OF HYDROGEN ION CONCENTRATION OF ACID WASTES
ON SOILS

I. INTRODUCTION AND SCOPE

Large volumes of strong inorganic and organic acid wastes are created as a result of industrial production.¹⁻⁷ The iron and steel industry, for example, is estimated to have generated over 1.2 billion gallons of spent "pickling" liquor from finishing and platings operations in 1976.¹ The most prominent strong acid-waste streams involve industrial electroplating and stripping. Some examples are

1. Waste-water treatment sludges
2. Spent cyanide plating bath solutions
3. Spent plating baths where cyanides are used
4. Spent metal stripping and cleaning bath solutions

Secondary lead waste leaching solutions also yield strong acids in large quantities. Strong sulfuric acid waste solutions are associated with copper refining. Fairly large quantities of organic acids such as formic, acetic, butyric, and propionic and carboxylic derivatives of organic compounds occur regularly in organic fluids and food processing wastes. Anaerobic waste impoundments of organic residues, such as those appearing in municipal solid waste (MSW) landfill leachates, generate a continuing supply of organic acids.

Only 3% of the spent acid wastes are deposited directly on land.⁸ The bulk of spent acid wastes (75%) are discharged to municipal sanitary sewers and an additional 12% appear in storm sewers.⁸ Because of the serious structural damage these acids impose on sewer systems, it is suggested that an alternative method of disposal be developed. Land disposal is one possibility, but we must be much more knowledgeable about soil/acid reactions and the consequence of longtime application of acids to land.

Subsurface waters accumulate soluble constituents from two main sources, namely, (1) the soil itself, through which rainwater must move, and/or (2) breakthrough of constituents present in solvents, leachates from solid wastes, and industrial waste streams. However, the soil not only functions as an absorbent, but as a barrier to movement of potential pollutants through soils. Soil as a porous material permits the movement of liquids at different rates to underground water sources. If the soil's capacity to retain (or attenuate) pollutants is exceeded, contamination will occur. The ability to predict soil attenuation of pollutants, soil permeability, and, finally, soil failure is an essential purpose for effective disposal on land whether disposal is made on the surface, in lagoons, behind soil barriers, or in excavated landfills. Predictions depend on precise quantitative information on effects of waste stream on soil characteristics that control permeability and attenuation.

The effects of acids on soils are considered to be largely associated with failure mechanisms.^{6,9} The failure of soil to retain pollutants in the presence of strong acids or soils treated with strong acids is due primarily to the solubilization of the clay mineral with the release of the structural aluminum and freeing of silica. Concurrent release of other clay mineral elements also occurs, resulting in porosity changes associated with the dissolution and altering effects on the exposed surfaces of soil pores and channels. Solubilization of clays by acids was found by Grim¹⁰ to vary with the

1. Concentration of acid
2. Kind of acid
3. Acid-to-clay ratio
4. Temperature
5. Time of contact

Carbonates and carbonate-containing minerals of both soils and geologic formations are readily susceptible to dissolution by acids. Such reactions accelerate channeling and permeability of soils, geological formations, and rock debris. The increase in permeability is well known and often referred to as acidulation. For example, organic acids such as acetic and formic have been used effectively to improve the fluid flow into oil wells¹¹ and through geologic formations.⁴ When carbonates of Ca, Mg, or Fe, for example, form encrusting barriers in wells or excavations where improved flow is desired, acids have been used as a solubilization agent. It has been suggested further¹² that chelating agents associated with the acids can aid in preventing reprecipitation of the Ca, Mg, and Fe solubilized.

Soil material reacts characteristically in a dilute acid leaching environment of certain cold-wet climates to form Spodosols.¹³ The podzolization process, as described by Jenny, consists of solubilization of the sesquioxides (oxides of Fe, Mn, and Al) and their migration from the A to B horizon leaving behind, in a less soluble state, "washed" quartz. Organic constituents of the soil move along with the sesquioxides and precipitate also in the B horizon. The knowledge of podzolization, therefore, provides clues as to what alterations might be expected when soils come in contact with acid wastes. The long-term effect of podzolization would, of course, be considerably shortened in the presence of the strong acid-waste streams from industry.

There is little consistency in the disposal of strong acids and the methods vary from industry to industry. Pretreatment to neutralize the acidity prior to land disposal is commonly practiced.^{14,15} Crushed limestone more recently has been researched as an economic material for neutralizing acid wastes.^{16,17} Its acid-neutralizing properties were used to advantage by Hoak et al.¹⁸ for spent pickling liquor neutralization and by Gehm¹⁹ for mine acid modification. Lime slurries have been under extensive investigation since the early 1970s for reduction of sulfur oxides and metal emissions from coal-burning industries.²⁰ Inexpensive natural clay and crushed limestone liners have been suggested^{15,21} to minimize movement of heavy metals from MSW landfill leachates.

Others who dispose of strong acids claim that strong acids react with the soil in such a way as to create a compacted layer below the soil surface that becomes sufficiently impermeable to inhibit further flow of fluids. At the present time, there is little agreement or consistency in the methods of strong acid waste disposals. Research literature is almost wholly lacking in quantitative data from which guidelines can be established.

Additional information is needed also on the effects of dilute acids, particularly sulfuric acid, and on soils as a result of acid rain. The primary acid in rainwater is sulfuric and hydrated sulfur oxides at pH levels as low as 2 and commonly at pH 3.0. Here again the effects of acid rain on the behavior of soil and soil constituents as it may influence the quality of groundwater has received small attention of a quantitative nature.

The method of presentation in this chapter purposefully deviates from that of others because it represents an extensive research study by the authors on a timely subject for which there is a poverty of information. Some preliminary information on the effects of dilute and concentrated acids on soil constituents related to the capacity of the soil to retain certain acids and their solubilized and potential polluting constituents is provided in an unpublished research report for the U.S. EPA from studies conducted at the University of Arizona. Data in the report relate to:

Table 1
TOTAL ANALYSIS OF SOILS FOR TRACE METALS AND FREE
IRON OXIDES

Soil series								"Free" Fe oxides (%)
Davidson c	4100	120	110	120	160	90	0.04	17.0
Molokai c	7400	310	320	600	260	410	0.04	23.0
Nicholson si c	950	50	130	135	65	68	0.06	5.6
Fanno c	280	45	70	100	60	38	0.07	3.7
Mohave (Ca) c l	770	50	120	120	200	40	0.03	2.5
Chalmers si c l	330	60	100	130	83	68	0.05	3.1
Ava si c l	360	50	77	110	80	55	0.05	4.0
Anthony si c l	275	50	55	80	200	25	0.06	1.8
Mohave s l	825	50	85	100	265	18	0.07	1.7
Kalkaska s	80	25	45	50	46	15	0.02	1.8
Wagram l s	50	bdl ^a	40	80	62	bdl ^a	bdl ^a	0.6

^a bdl, below detectable limit.

1. The effects of deionized water, dilute acids (e.g., acid rain), dilute acid reduction/oxidation solutions, and acid MSW leachates on soil permeability and movement of native soil constituents
2. A comparison of the permeability of different soils receiving concentrated reagent grade acids, 2 N HNO₃, H₂SO₄, CH₃COOH, and 6 N and 8 N H₃PO₄
3. A comparison of different industrial spent-acid waste streams of HNO₃, H₂SO₄, and H₃PO₄ on the permeability of different soils
4. The migration rates through different soils of polluting constituents carried by acid waste streams
5. The nature of the reactions between the soil constituents and the acids that contribute to failure of soil to contain acid waste streams and their constituents

II. MATERIALS AND METHODS

A. Materials

1. Soils

Thirteen soils representative of 7 of the 10 major soil orders of the world were collected throughout the United States. Selected properties of these soils (Chapter 8, Table 3) indicate they range from acid (pH 4.2 for an Ultisol, Wagram) to alkaline (pH 7.8 for an Aridisol, Anthony sandy loam). The clay* ranged from 1 to 52% and cation exchange capacity (CEC) from 2 to 37 meq/100 g. The clay mineral composition of the <2 µm separate varied considerably with no pure species dominating completely. The total Co, Cr, Cu, Mn, Ni, and "free" Fe oxides appear in Table 1. The riverbottom sand was included to illustrate what occurs when gravelpits and riverbeds are used for disposal.

The soils were collected from the B horizon, when present, or from a depth greater than 30 cm.²² This soil selection was made in order to emphasize mineral characteristics without the possible confounding effects of organic matter. Thus, if others wish to characterize a soil-like material for covering, enveloping, cell encasement, they can take note of the

* The soil textural class has been abbreviated throughout the text as follows: s, sand; si, silt; c, clay; l, loam. Combinations occur as s c l for sandy clay loam and si c l for silty clay loam. Sands vary in size from 2 to 0.05 mm, silts vary from 0.05 to 0.002 mm, and clay is less than 0.002 mm.

Table 2
TOTAL CARBON AND SELECTED METAL CONTENTS ON SPENT
INDUSTRIAL ACIDS

Element	Spent-acid source			
	Sylvania™ nitric acid (µg/g)	Wolverine™ nitric acid (µg/g)	Cyprus Bagdad™ sulfuric acid (µg/g)	Phosphoric acid, 8.8 N (µg/g)
Aluminum, Al	304.0	74.0	2,340.0	16,931.0
Boron, B	595.0	336.0	0.9	nd ^a
Calcium, Ca	0.7	3.0	498.0	nd
Cadmium, Cd	3.0	2.0	1,000.0	10.2
Cobalt, Co	0.2	0.8	17.0	<1.0
Copper, Cu	2,400.0	26,700.0	1,083.0	49.3
Chromium, Cr	3.0	5.5	1.0	6.5
Iron, Fe	402.0	477.0	1,662.0	48.7
Lead, Pb	15,808.0	9,747.0	0.5	32.8
Manganese, Mn	2.3	3.1	234.0	<0.05
Mercury, Hg	1.0	2.0	0.1	1.0
Nickel, Ni	9.3	42.6	11.0	10.6
Phosphorus, P	188.6	129.0	20.0	204,326.0
Potassium, K	100.0	nd	212.0	nd
Silica, Si	283.0	276.0	212.0	37.4
Sodium, Na	103.0	100.0	216.0	109.0
Titanium, Ti	32.0	1,043.0	0.3	58.7
Zinc, Zn	2,850.0	1,477.0	54.0	8.6
Zirconium, Zr	12.1	1,937.0	0.5	nd
Total carbon, C	92.0	116.0	~10.0	92.0
Nitrate, N (%)	12.0	10.7	0.5	2.1
Total-dissolved solids, TDS (%)	14.7	13.2	15.1	13.8
Normality, N	2.0	2.0 N	1.0 N	8.3 N and 6.0 N

^a nd, not determined.

^b Determined by evaporation in an oven at 60°C and finally at 21°C by vacuum drying. Thus, both metal salts and acid are included. Sylvania™, for example, has only 2.3% metals.

characteristics of the most similar soil material used in this study and estimate the attenuation characteristics of their material.

The native montmorillonite-type clay (99% smectite) used was identified by X-ray analysis. It was not further characterized and, therefore, does not appear in Table 1. The raw mined "Gila clay" from Arizona possessed some natural structure which permitted ready permeability to water (1 cm/hr) even when compacted in soil columns.

2. Acids (Reagent Grade)

Reagent grade HNO₃, H₂SO₄, H₃PO₄, and CH₃COOH were diluted with deionized water (DW) to provide acid concentrations equivalent to those of the spent wastes. The resulting acids were 2 N, 2 N, 6 N, and 2 N, respectively. An additional H₂SO₄ solution also was prepared at a pH of 3.0 to be representative of acid rain.

3. Spent Acid Wastes

Two nitric acid waste streams were represented by industrial spent acids from Sylvania™ and Wolverine™ (Table 2). Spent sulfuric acid was obtained by courtesy of the Cyprus-

Table 3
SELECTED CHEMICAL
CONSTITUENTS OF THE
MSW LEACHATE USED

Constituent	Concentration ppm
TOC	8,400.00
Ca	1,600.00
Co	0.20
Cr	0.25
Cu	0.20
Fe	873.00
Mg	176.00
Mn	15.50
Na	684.00
Ni	0.40
Zn	14.00
pH	5.00
EC(mmhos/cm)	13.5

Bagdad™ Copper Mining Co. of Bagdad, Arizona. The phosphoric acid waste stream had a concentration of about 8.8N and came from a combination of five H_3PO_4 industrial wastes used for automobile parts brightening. Phosphoric acid was studied both at 8.8 and 6 N levels. A simulated acid waste of 0.025 M AlCl_3 plus 0.025 M FeCl_2 with enough HCl added to adjust the pH to 3.0 was prepared for comparative purposes. The $\text{AlCl}_3 \cdot \text{FeCl}_2$ solution was expected to provide data on the effects on soils of a very strongly buffered acid and a readily oxidizable leachate.

4. MSW Leachate

Leachate from municipal solid waste (MSW) was generated in a 4000-ℓ commercial steel tank. This tank was sealed with epoxy, packed with representative municipal refuse, and immediately saturated with water. The first leachate samples were drawn from the bottom of the tank 6 months after packing and preserved under CO_2 at all times to prevent precipitation of important constituents (Table 3).²³

B. Methods

1. Soil Columns

The air-dried soils were passed through a 2-mm sieve and then uniformly packed (to approximately field bulk density) into three sizes of PVC cylinders (10×20 ; 5.1×20 ; or 6.1×35.5 cm) for migration studies. The flow for dilute acids at pH 3.0 and deionized water was adjusted to one half pore volume (pv) per day and was flushed with N_2 gas to keep O_2 exposure at a minimum during the leaching process. The dilute acid columns were leached until 15 or more pore volumes had passed through the soil. The Al-Fe solution was allowed to flow until the effluent concentration of Al and Fe equaled that of the influent (i.e., $c/c_0 = 1$, where c is the effluent concentration and c_0 the influent).

The gravity flow rate of the concentrated acids 2 N or higher was not adjusted because of the slow movement ($< 1/2$ pore volume per day). The acid columns were open to the atmosphere. A head of 10 cm of solution above the soil surface was maintained to permit some comparative evaluation of penetration rates of the different acids and spent waste streams. The effluent was collected at such time intervals, depending on rate of flow, that would allow an accurate measurement of permeability. The rate of wetting front due to

addition of the acids to soils was measured frequently by observation through the sides of the glass columns.

2. *Effluent Analyses*

Total acidity was obtained by titration with standardized NaOH. Emission spectroscopy involving the D.C. argon plasma furnace* of Spectrospan III was used for Al, B, Ca, Cd, Cr, Cu, Fe, K, Ni, Mg, P, Pb, Si, Ti, and Zn determinations. Emission spectroscopy involving the air-acetylene flame method was used for Na. Atomic absorption spectroscopy was used to analyze for Mn, Co, and Mo. All standards contained 1% HNO₃ acid. The lower level of detection was at 0.5 ppm for all elements (except Mo which was 1 ppm) due to the unusual complex and acid nature of the effluents. All standards contained 50 ppm of each Na, K, Ca, and Mg salts to minimize interferences from the total elemental analysis of the spent acid used.

3. *Soil Analyses*

The methods of analysis for soils followed those given in detail in Chapter 4.

III. EFFECT OF WATER, DILUTE ACIDS, AND MSW LEACHATES ON SOILS

A. *Water*

Surface water from rainfall or irrigation that percolates into the soil and finally reaches the capillary fringes of underground sources carries soluble salts. The concentration of dissolved solids reaching the groundwater depends on the levels of these constituents in (1) the water itself and (2) the soil. Although the concentrations are usually small, the soil contributes substantially to the quality of subsurface water and has an impact on water quality, particularly where salty waters are involved in recharge.

Data in Table 4 reveal that, indeed, common cations and anions can be solubilized by water leaching through the soil. Only the maximum concentrations are reported due to the voluminous nature of the data. Solubilization reached a maximum in the first pore volume displacement and declined to a minimum as each pore volume of water was displaced. The trend was for the concentration to stabilize after about four or five displacements in sandy soils and seven to ten displacements in clay soils. Organic substances were found in significant amounts only in the podzolic Kalkaska sand leachings. The electrical conductivity of the soil leachates indicate that all soils may be expected to contribute a considerable amount of dissolved solids or salts to underground waters.

The pH level of soils from arid lands (Anthony, Fanno, and Mohave) decreased as leaching progressed, whereas it increased for soils from humid climates.

Heavy metals were not detected in the soil solutions in appreciable levels by the method used (i.e., Atomic Absorption) (Table 5). Yet, the electrical conductivity gives an overall indication. The USDA staff suggests that a reasonable estimation of salts (total dissolved solids) may be calculated by multiplying electrical conductivity by a constant factor, such

* The detection limits for the elements are

Cd	8 ppb × 15 = 120 ppb
Zn	2 ppb × 15 = 30 ppb
Fe	3 ppb × 15 = 45 ppb
Cu	2 ppb × 15 = 30 ppb
Ni	2 ppb × 15 = 30 ppb
Cr	2 ppb × 15 = 30 ppb

(Published detection limits using the plasma emission spectrometers.)

Table 4
CONCENTRATION OF SOME COMMON CATIONS AND ANIONS IN THE
SOIL-SOLUTION DISPLACEMENTS FROM COLUMNS RECEIVING
DEIONIZED WATER

Soil series	Soil solution			Common elements ($\mu\text{g/g}$)							
	pH	Electrical conductivity,		K	Na	Ca	Mg ($\mu\text{g/g}$)	Cl	NH_4	P	Si
		EC ($\mu\text{mhos/cm}$)	TDS (salt)								
Davidson c	6.0—6.8	303	194	2	5	35	14	27	0.2	bdl ^a	0.2
Molokai c	7.1—7.8	1500	960	20	107	105	58	320	5.0	bdl	1.3
Nicholson si c l	6.4—7.1	180	115	1	20	15	3	24	1.6	bdl	2.0
Fanno c	7.2—7.7	370	237	5	21	39	12	bdl	bdl	bdl	0.7
Mohave (Ca) c l	7.4—7.0	430	275	4	25	200	22	20	0.3	bdl	0.9
Chalmers si c l	7.0—7.4	310	198	1	12	37	12	17	0.4	bdl	8.0
Ava si c l	4.8—5.3	160	120	3	8	5	7	22	0.2	bdl	2.8
Anthony s l	6.8—7.5	330	211	14	10	53	3	11	0.8	3.6	1.3
Mohvae s l	6.7—8.0	850	544	15	79	170	22	28	1.6	5.0	1.6
Kalkaska s	4.5—5.0	200	128	8	6	17	3	11	2.6	bdl	0.3
Wagram l s	5.3—6.2	270	173	11	15	26	2	31	0.5	bdl	0.6

Note: Data represent maximum constituents found in any l of 28 pore volume displacements.

^a bdl, below detectable limits.

Table 5
MAXIMUM CONCENTRATION OF SOME TRACE METALS IN
THE SOIL-SOLUTION DISPLACEMENTS FROM COLUMNS
RECEIVING DEIONIZED WATER^a

Soil series	Original soil pH	Al ($\mu\text{g/g}$)	Cu ($\mu\text{g/g}$)	Fe ($\mu\text{g/g}$)	Mn ($\mu\text{g/g}$)	Zn ($\mu\text{g/g}$)
Davidson c	6.2	bdl ^b	bdl	bdl	0.20	bdl
Molokai c	6.2	bdl	0.8	0.3	2.00	bdl
Nicholson si c l	6.7	bdl	bdl	0.3	bdl	bdl
Fanno c	7.0	bdl	bdl	bdl	<0.05	bdl
Mohave (Ca) c l	7.8	bdl	bdl	bdl	bdl	bdl
Chalmers si c l	6.6	bdl	bdl	bdl	0.10	bdl
Ava si c l	4.5	1	bdl	bdl	0.10	0.50
Anthony s l	7.8	5	bdl	0.3	<0.05	bdl
Mohave s l	7.3	bdl	bdl	0.2	2.00	bdl
Kalkaska s	4.7	4	bdl	6.0	0.20	0.05
Wagram l s	4.2	1	bdl	0.4	0.85	<0.005

^a Data represent maximum constituents for any l of 28 pore-space displacements. Trace elements not detected in any soil leachate are Cd, Co, Cr, Ni, and Pb.

^b bdl, below detectable limits of the Atomic Absorption method used. The detectable limits for the Atomic Absorption method used (in $\mu\text{g/l}$) are Cd, 0.005; Cr, 0.1; Co, 0.05; Cu, 0.05; Pb, 0.5; Ni, 0.05; Mn, 0.05; Zn, 0.005; Al, 0.5; and Fe, 0.1.

Table 6
MAXIMUM CONCENTRATION OF SOME COMMON CATIONS AND ANIONS IN THE
SOIL-SOLUTION DISPLACEMENTS FROM COLUMNS RECEIVING WATER ACIDIFIED
WITH H₂SO₄ to pH 3.0^a

Soil series	Soil solution			Some common cations and anions in effluent from soil columns (µg/g)							
	Final pH	Electrical conductivity (µmhos/cm)	TDS (salts)	K	Na	Ca	Mg	Cl	NO ₃ -N	P	Si
Davidson c	4.4	230	147	17	16	18	9	25	13.0	bdl ^b	4
Molokai c	5.0	3,250	2,080	171	167	165	195	700	1.0	bdl	30
Nicholson si c	5.0	170	109	10	22	13	3	9	2.0	1.3	30
Fanno c	6.0	360	230	30	23	40	11	14	3.0	bdl	14
Chalmers si c l	5.6	400	256	58	7	38	15	44	1.2	0.25	10
Ava si c l	4.6	190	122	14	9	12	5	32	0.2	bdl	30
Mohave s l	6.0	1,600	1,024	104	77	142	8	42	0.4	1.8	24
Anthony s l	5.8	707	452	118	20	97	16	28	0.5	0.7	19
Kalkaska s	4.6	240	154	37	8	16	2	37	0.5	bdl	11
Wagram l s	4.4	240	154	89	9	11	2	25	1.6	0.12	5

^a All soils data represent ranges of constituents for ~15 pore-space displacements.

^b bdl, below detectable limit.

Table 7
MAXIMUM CONCENTRATION OF SOME TRACE ELEMENTS IN THE
SOIL-SOLUTION DISPLACEMENTS FROM COLUMNS RECEIVING DILUTE
H₂SO₄ AT pH 3.0^a

Soil	Final leachate pH	Al (μg/g)	Cu (μg/g)	Cd (μg/g)	Fe (μg/g)	Mn (μg/g)	Ni (μg/g)	Zn (μg/g)
Davidson c	4.4	8.0	22	0.007	0.38	0.47	bdl ^b	0.14
Molokai c	5.0	0.6	19	0.001	0.60	2.30	0.11	0.19
Nicholson si c	5.0	bdl	bdl	bdl	<0.001	0.32	bdl	0.21
Fanno c	6.0	bdl	bdl	bdl	0.15	0.43	bdl	0.01
Chalmers si c l	5.6	4.0	0.11	0.12	0.44	0.25	0.15	0.25
Ava si c l	4.6	3.1	0.08	0.01	0.90	0.75	bdl	0.15
Mohave s l	6.0	bdl	0.33	bdl	1.20	1.80	bdl	0.06
Anthony s l	5.8	1.1	0.39	bdl	0.58	0.31	bdl	0.12
Kalkaska s	4.6	5.0	0.13	0.01	0.23	0.20	bdl	1.30
Wagram l s	4.4	1.2	0.12	0.01	7.40	0.66	0.09	0.003

^a Data represent ranges of constituents for ~15 pore-space displacements. Trace elements not detected in any soil leachate are Co, Cr, and Pb.

^b bdl, below detectable limits for the Atomic Adsorption method used.

as, $EC \times 10^6 \times 0.64 = \text{ppm soluble salts}$.²⁴ Table 4 reports these kinds of data. The maximum TDS for any one pore volume displacement ranges from a low of 120 ppm in a sandy soil to a high of 960 ppm in a clay soil.

B. Sulfuric Acid at pH 3.0

About the same maximum constituent levels were eluted during the 28 continuous pore-space displacements by aqueous H₂SO₄ at pH 3.0 except for Molokai c and the arid land sandy loams, Mohave and Anthony (Table 6). About twice as many total soluble salts (TDS) were released with the dilute acid as with deionized water. Soils possess a remarkable buffering capacity against change in pH. The effluent from three soils (Davidson clay, Nicholson silty clay, and Anthony sandy loam) dropped only between 1.7 and 2.0 units, four other soils dropped about 1 unit, and the pH change in effluent from the three most acid soils (pH 4.2 to 4.7) was insignificant.

The Al, Fe, and Zn of the soils were more readily solubilized and eluted more extensively with the column effluent during the dilute acid leaching as compared with other metals and with the same elements from the deionized water leaching over the same period (Table 7). There is some evidence indicating that Cd, Cu, Mn, and Ni also were made slightly more mobile by the dilute acid leachate than by deionized water (Table 7). Neither Cd nor Ni appeared in the deionized water effluents, but both were found in several of the dilute acid leachings. The general trend was for the concentrations not to change appreciably in the acid effluent as leaching progressed. In this respect, dilute acid leaching differs from that of water alone.

C. AlCl₃-FeCl₂ at pH 3.0

Leaching of soils with an aqueous solution of 0.025 M AlCl₃ and FeCl₂ adjusted to pH 3.0 was also done. The experiment continued until total breakthrough of Al and Fe occurred (i.e., when $c/c_0 = 1$, where c_0 is the concentration of the influent Al and Fe and c the effluent concentration). Breakthrough was more related to the particle size distribution of the soil than any other factor. The pH of the soil, also, was highly important. At about the same pH, soils having a greater amount of clay retained Al and Fe better than coarse-textured

sandy soils. On the other hand, Al and Fe were least mobile in the near neutral to alkaline soils and most mobile in acid soils. Breakthrough for the 20-cm columns of Wagram and Kalkaska sandy and Ava silty clay loam occurred between 4 and 7 pvd as compared with 20 to 26 pvs for the less acid Molokai clay, Chalmers silty clay loam, and Nicholson silty clay.

Also to be noted, both the common ions (Table 8) and heavy and trace metals (Table 9) were solubilized and moved to a much greater extent with the Al-Fe dilute aqueous solution than with either dilute H_2SO_4 or water alone. The metals Co, Cr, and Pb which were not detected in the soil-column effluents receiving dilute H_2SO_4 or water alone were found to be solubilized and moderately mobile with the Al-Fe leachate. Other heavy metals such as Cd and Ni also were released from the soil in a soluble and mobile form by the Al-Fe solution at pH 3.0 (Table 9) in modest amounts of 0 to 0.12 and 0 to 0.15 $\mu\text{g/g}$. The pH level of the soil appears to differentially influence the rate of movement of Al and Fe as individual ions (Figure 1). In the pH range of 4 to 5, breakthrough for both elements takes place at about the same time, whereas within the pH range of about 5 to 6.5, Fe appears to break through more slowly than Al. Within the neutral to slightly alkaline range, Al appears to be less mobile than Fe.

Compared with the H_2SO_4 solution and water alone, the Al-Fe solution is much more highly reducing, higher in soluble salts, and higher in chloride ions. All of these factors contribute to the apparent greater dissolution and solubilization of soil constituents and migration rate of the influent Al and Fe metals (Tables 8 and 9).

D. Municipal Solid Waste Landfill Leachate

The concentration of heavy metals in the effluent from soils receiving municipal solid waste (MSW) landfill-type leachate was not significantly different from that of soils leached with deionized water for 28 pvd, despite the fact that the MSW leachate pH was at 5.0 (Table 10), and the salts and organic carbon content were relatively high. The levels of heavy and trace metals were lower than those added in the leachate, indicating that attenuation was taking place quite efficiently. The total organic carbon, however, appeared at breakthrough levels after only a few pore volume displacements, indicating that organic constituents of the MSW leachate were more mobile than inorganic ions. Phosphorus only occasionally appeared in the column effluents in measurable amounts.

Measurable levels of common ions (Ca, Mg, Na, K, and Cl) appeared in the soil column effluents prior to that of the trace and heavy metals (Tables 10 and 11). The common ions from the MSW leachate treatment moved through the soil at only slightly higher levels than those solubilized from water alone (Tables 4 and 11). However, the levels of salts were below the combined amounts attributable to those solubilized by water plus those added in the MSW leachate influent (Tables 3 and 11) during the 28 pvd. The clay soils retained all constituents better than the sandy soils (Table 11).

The pH of the effluents of the soil columns receiving MSW leachate increased slightly for the most acid soils, but decreased slightly for the neutral and alkaline soils.

IV. EFFECTS OF STRONG INORGANIC ACIDS ON SOIL

Strong acids, whether inorganic or organic, have been demonstrated to alter permeability and infiltration of fluids through soils. The limited research reported on strong acid/soil interaction originates more from batch than column-type studies. Soil columns take into account downward migration not only of soluble constituents in the original waste stream, but dissolved soil constituents in the solution. In addition, infiltrations of insoluble constituents, salts, and precipitates will tend to plug tortuous soil pore channels.

This section reports results for relatively long (i.e., 20, 30, and 36 cm) columns of soil.

Table 8
MAXIMUM CONCENTRATION OF SOME CATIONS AND ANIONS IN THE SOIL-SOLUTION
DISPLACEMENTS FROM COLUMNS RECEIVING 0.025 M AlCl_3 AND FeCl_3 SOLUTION AT A pH OF 3.0

Soils	Breakthrough pore volume displacements (pvd)	Soil solution		Some common ions from the soil column effluent							
		Final pH	Electrical conductivity ^a (EC) ($\mu\text{mhos/cm}$)	TDS ^b (salts) ($\mu\text{g/g}$)	K ($\mu\text{g/g}$)	Na ($\mu\text{g/g}$)	Ca ($\mu\text{g/g}$)	Mg ($\mu\text{g/g}$)	Cl ($\mu\text{g/g}$)	P ($\mu\text{g/g}$)	Si ($\mu\text{g/g}$)
Davidson c	17	3.4	16,500	10,560	142	13	770	510	4,200	0.03	22
Molokai c	26	3.6	9,000	5,760	780	280	110	880	4,100	0.30	62
Nicholson si c	23	3.3	9,200	5,900	40	150	1,500	440	4,200	bdl ^c	42
Fanno c	12	3.4	9,600	6,150	200	86	1,200	600	4,700	bdl	34
Chalmers si c l	20	3.4	21,000	13,400	28	32	1,500	680	4,500	bdl	27
Ava si c l	4	3.2	10,000	6,400	100	37	470	600	4,300	bdl	42
Anthony s l	14	3.5	8,100	5,180	800	62	1,700	780	4,200	bdl	50
Mohave s l	19	3.4	7,900	5,060	490	300	420	59	4,300	0.24	59
Kalkaska s	6	3.2	7,800	5,000	170	15	400	400	4,200	bdl	12
Wagram l s	7	3.6	8,100	5,184	290	28	200	25	4,200	bdl	3

^a EC, electrical conductivity of the soil column effluent.
^b TDS, total dissolved solids or soluble salts.
^c bdl, below detectable limits.

Table 9
MAXIMUM CONCENTRATION OF SOME HEAVY METALS IN THE SOIL-SOLUTION
DISPLACEMENTS FROM COLUMNS RECEIVING 0.025 M AlCl_3 AND FeCl_2 SOLUTION AT
A pH OF 3.0

Soil	Pore-space displacement ($c/c_0 = 1$)	Al ($\mu\text{g/g}$)	Fe ($\mu\text{g/g}$)	Cd ($\mu\text{g/g}$)	Co ($\mu\text{g/g}$)	Cr ($\mu\text{g/g}$)	Cu ($\mu\text{g/g}$)	Mn ($\mu\text{g/g}$)	Ni ($\mu\text{g/g}$)	Pb ($\mu\text{g/g}$)	Zn ($\mu\text{g/g}$)
Davidson c	17	860	1080	94.00	11.0	2.8	0.9	950	0.7	bdl	0.6
Molokai c	26	775	240	0.70	26.0	0.7	6.6	1,400	34.0	bdl	13.0
Nicholson si c	23	516	1400	0.10	4.7	bdl ^a	bdl	150	1.8	0.5	1.6
Fanno c	12	550	1460	0.04	0.6	bdl	bdl	40	0.6	0.4	0.6
Chalmers si c l	20	530	1900	0.10	3.8	0.1	0.3	365	6.0	0.3	0.9
Ava si c l	14	610	1200	bdl	2.1	bdl	0.7	23	1.0	0.4	1.0
Anthony s l	14	600	1800	0.09	2.0	bdl	0.7	220	1.5	0.4	1.3
Mohave s l	19	610	1550	0.04	2.2	bdl	bdl	225	1.3	0.7	0.2
Kalkaska s	6	610	1540	0.70	0.2	bdl	bdl	6	0.8	bdl	3.3
Wagram	7	635	1580	0.07	0.3	bdl	0.2	18	1.1	0.5	0.6

^a bdl, below detectable limits.

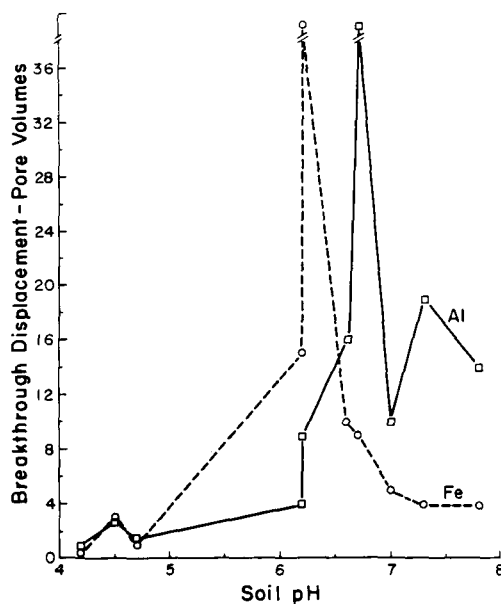


FIGURE 1. The relationship between the soil pH values and pvds occurring before either Al or Fe effluent concentration equaled that of the influent. (From Fuller, W. H., Korte, N. E., Niebla, E. E., and Alesii, B. A., *Soil Sci.*, 122, 231, 1976. With permission.)

Table 10
MAXIMUM CONCENTRATION OF SOME TRACE
AND HEAVY METALS IN THE SOIL-SOLUTION
DISPLACEMENTS FROM COLUMNS RECEIVING
NATURAL MSW LANDFILL LEACHATE^a

Soil	Al ($\mu\text{g/g}$)	Cd ($\mu\text{g/g}$)	Fe ($\mu\text{g/g}$)	Mn ($\mu\text{g/g}$)	Zn ($\mu\text{g/g}$)
Davidson c	bdl ^b	0.001	bdl	0.8	0.5
Molokai c	0.5	bdl	bdl	2.5	0.5
Nicolson si c	1.5	bdl	bdl	0.7	bdl
Fanno c	bdl	bdl	bdl	0.3	bdl
Mohave (Ca) c l	bdl	bdl	bdl	0.1	bdl
Chalmers si c l	bdl	bdl	bdl	0.2	0.9
Ava si c l	8.8	bdl	1.5	0.6	0.2
Anthony s l	bdl	bdl	2.2	6.2	1.5
Mohave s l	bdl	bdl	0.2	3.0	bdl
Kalkaska s	11.2	bdl	3.9	3.0	5.5
Wagram l s	4.5	bdl	7.5	4.2	1.9

^a All soil data represents maximum concentration for 28 pore-space displacements. Metals not detected in any soil-column effluent are; Co, Cu, Cr, Pb, and Ni.

^b bdl, below detection limits.

Table 11
MAXIMUM CONCENTRATION OF SOME COMMON CATIONS AND
ANIONS IN THE SOIL-SOLUTION DISPLACEMENTS FROM COLUMNS
RECEIVING NATURAL MSW LANDFILL LEACHATE^a

Soil	Soil solution			Common ions found in soil column effluents ($\mu\text{g/g}$)						
	Final pH	Electrical conductivity ($\mu\text{mhos/cm}^3$)	TDS ^b (salts)	K	Na	Ca	Mg	Cl	P	Si
Davidson c	6.7	2250	1440	160	75	130	56	105	bdl ^c	3
Molokai c	6.8	3100	1980	140	170	157	157	296	bdl	18
Nicholson si c	6.8	1875	1200	4	85	205	83	96	bdl	26
Fanno c	6.6	2000	1280	14	65	190	95	105	bdl	8
Mohave (Ca) c l	6.9	2250	1440	10	160	275	27	159	5	22
Chalmers si c l	6.9	1700	1090	2	70	175	75	45	bdl	13
Ava si c l	4.9	1150	736	120	75	105	48	132	bdl	31
Anthony s l	7.0	2300	1470	175	73	175	57	111	3	21
Mohave s l	6.8	2600	1660	98	160	175	59	102	bdl	29
Kalkaska s	6.3	1640	1050	140	77	105	13	132	bdl	23
Wagram l s	6.9	2150	1376	175	73	140	27	156	19	9

^a All soils data represent maximum concentration for 28 pore-space displacements.

^b TDS = total dissolved solids.

^c bdl = below detectable limits.

The soil-acid interaction is studied with pure acid alone in the absence of interfering wastes characteristically associated with industrial spent-acid waste streams, in order to isolate and identify strictly acid effects. The data may then provide a basis for interpretation of the more practical phases involving actual industrial spent-acid waste streams.

A. Nitric Acid at 2 N

1. Column Flow Characteristics

The most rapid flow rate with nitric acid through dry-packed nonsaturated soil occurred in the Mohave (Ca) clay which, after some swelling (from a length of 20 to 22 cm), began to elute within 3 hours with a head of 17.5 cm. The slowest wetting front movement was in the Nicholson si c columns which also swelled 2 cm in the 6×20 cm column and began flowing after 190 hours. Ava si c l and Davidson c were intermediate in wetting front with the intake flow rates of 18 and 79 cm/d prior to elution, respectively. Soil expansion of about 0.5 cm occurred in both of these columns. The expansion undoubtedly reduced the original soil pore space.

The flow rate varied considerably within each column. The general trend in all columns was one of marked decreasing flow rate as increasing amounts of acid passed through. Mohave (Ca) had the highest average flow rate varying from as high as 4.2 to 0.54 cm/d after 3.2 pvd. The slowest flow column was Nicholson with relatively slow rates of 0.16 to 0.12 cm/d for 0.5 pvd. Nicholson si c stopped flowing liquid after about 0.5 pvd. Ava and Davidson had intermediate flows ranging from 1.07 to 0.40 and 0.57 to 0.31 cm/d after 1.5 and 2.2 pvd, respectively. Clearly, the passage of acid through these four soils did not improve on the natural structure of the soil, probably due to a breakdown of the organic matter, clay minerals, metal oxides, carbonates, and other aggregate cementing agents, with accompanying dispersion of soil particles and clogging of pores.

Table 12
THE SOLUBILIZATION AND MOVEMENT OF CONSTITUENTS FROM FOUR SOILS LEACHED WITH 2 N
NITRIC ACID

Soil constituent ^b pvd ^{1,c}	Amount of soil constituent eluted ^a (μg)													
	Davidson clay				Mohave (Ca) clay loam				Ava silty clay loam				Nicholson si c	
	0-0.05	0.05-1	1-1.5		0-1	1-2	2-3		0-0.5	0.5-1	1-1.5		1.5-2	0-0.25 0.25-0.5
B	121	100	46		108	214	310		162	175	970		714	50 68
P	73	104	212		119	bdl	bdl		751	722	3,387		8,349	0.1
Co	1,442	4,782	10,263		512	546	874		4,096	2,998	1,793		1,346	120 162
Cu	97	96	318		166	169	249		1,636	3,544	2,459		1,694	39 53
Cr	0.1	0.1	0.1		0.1	0.1	0.1		0.1	511	1,916		1,052	53 77
Ni	225	348	681		679	493	2,772		819	774	1,800		1,487	185 303
Zn	59	301	1,307		0.5	0.5	0.5		485	475	615		510	68 101
Fe × 10 ²	1.6	1.3	1.7		3.5	3.6	4.1		9.6	159	123		173	0.7 1.0
Al × 10 ²	7,932	19,718	31,685		18	26	180		14,630	19,212	21,995		16,644	27 20
Si × 10 ²	72	75	77		75	105	116		95	131	297		323	20 32
Mn × 10 ²	3,272	3,224	3,300		19	197	288		1,819	1,284	724		370	31 56
Na × 10 ²	128	40	37		137	280	264		408	36	42		20	753 783
K × 10 ²	1,075	637	490		294	316	463		408	475	527		456	17 27
Ca × 10 ³	1,867	203	93		579	6,611	10,213		649	106	1,508		90	1,276 3,560
Mg × 10 ³	94	5	2		183	459	1,287		297	81	1,596		132	124 164

^a 1 Migration virtually came to a halt after about 1/2 pvd.
^b 2 Cd, Pb, Mo, and Ti were below detectable limits of 0.1 μg/ℓ in the soil-column effluents.
^c 3 One pvd (pore volume displacement) for the Davidson c = 494 mℓ; for Mohave (Ca) c = 469 mℓ; for Ava si c l = 489 mℓ; and Nicholson si c = 431 mℓ.

2. *pH of Soil Column Effluent*

The soil with the highest buffering capability was Mohave (Ca) which had an eluate pH of 6.5 at a pvd of 0.5 and pH of 3.3 after 3.3 pvd. The Nicholson si c eluate also was changed little, but due to its very slow permeability, only 0.5 of a pvd was obtained with an effluent pH of about 6.2. The Davidson effluent had a pH of 3.1 at pvd of 0.5 and pH of 2.0 at pvd of 2.2.

3. *Movement of Soil Constituents*

Nitric acid at 2 *N* has a great corrosive effect on soil with accompanying dissolution and movement of natural constituents when applied to air-dry soils (Table 12). All four soils released large amounts of heavy metals, common soil solution ions such as Ca, Mg, Na, and K, and mineral structural Al and Si. Although each of these groups were well represented in the soil column effluents, quantitative levels varied from soil to soil presumably because of differences in primary and secondary minerals inherent in the soils themselves. For example, Ca and Mg released from the arid-zone soil (Mohave) far exceeded that from soils of humid climates yet Co was found in effluents from the Davidson c (a humid-zone soil) in levels up to ten times as great as from Mohave c l (Table 12).

The calcareous Mohave c l (pH 7.8) behaved quite differently from the other soils not containing free calcium and magnesium carbonate. There was less solubilization and movement of metals (except for Ca and Mg) at similar pore space displacements by the nitric acid treatment than for the other soils. The Mohave carbonates undoubtedly neutralized much of the acid as evidenced by the comparatively abundant Ca and Mg in the effluent. The most acid soil, Ava si c l (pH 4.5), was the most susceptible to the failure action of strong nitric acid. This is evidenced by the highest mobility of most constituents, cf. Al, Fe, Si, P, and Cr, Cu, and Ni. Davidson c (pH 6.2) is abundantly supplied with native oxides of Mn. The nitric acid solubilized large quantities of Mn to the soil solution (Table 12). Zinc appeared quite mobile early in the Davidson clay and Ava silty clay loam effluents as compared with Mohave clay loam. Cadmium, Pb, Mo, and Ti were not mobilized in this early stage by the nitric acid.

The data presented represent just the initial effect of nitric acid since liquid movement through the soils virtually stopped after pore volume displacement of 0.5, 1.5, 3.0, and 2.2 had taken place in Nicholson si c l, Davidson c, Mohave c l, and Ava si c l, respectively. The pores of the soil appeared to be plugged with fine soil particles and salts, due to reactions between the strong HNO_3 and the soil, according to petrographic examinations.

B. *Sulfuric Acid at 2 N*

1. *Column Flow Characteristics*

The application of 2N H_2SO_4 to four clay soils significantly affected the soil permeability and drastically reduced the flow rates within the first pvd. It took 240, 12.5, and 6 hours to completely wet the 6×20 -cm column of air-dry Davidson c, Ava si c l, and Mohave (Ca) c l soils, respectively. Nicholson si c did not become completely wet with the acid in 24 months. The first 50 ml of liquid eluted at average rates of 0.40, 0.82, 3.0, and 0 cm/d for Davidson c, Ava si c l, Mohave (Ca) c l, and Nicholson si c, respectively. These values decreased to 0.20, 0.45, 0.06, and 0 cm/d during the last 50 ml eluted before stopping for the same soils, respectively. All of the soils exhibited swelling.

The soil column height changed from 20 to 24.5, 23.0, 21.0, and 20.3 cm for Mohave (Ca) c l, Nicholson si c, Davidson c, and Ava si c l, respectively, as a result of the reactions between the soils and 2 N H_2SO_4 .

2. *pH of Soil Column Effluent*

As a result of applying 2 N H_2SO_4 , the pH of the soil column effluent dropped in all soils

but Mohave c l which remained unchanged. At the time of flow cessation, the elutes had developed pH levels of 2.8 and 3.4 for Ava si c l and Davidson c, respectively.

3. Movement of Soil Constituents

The solubilization and movement of constituents from the four soils receiving 2 *N* sulfuric acid may be ascertained from data in Table 13. Again, the strong mineral acid solubilized and moved considerable metals through the 20 cm of soil. Metal movement for Nicholson is not available as it did not pass effluent. The great contrast between the arid-zone soil Mohave c l and Ava si c l, an acid humid-zone soil, again demonstrates a significant difference associated between soil variables of pH and carbonate content. In fact, Fe did not appear except in trace amounts in Mohave c l effluent, and Al and Si were only slightly mobile as compared with the Ava soil. Manganese, also, was least soluble in the soil solution of the Mohave c l. Relatively high levels of all three elements appear in the last one third pvd of the Ava si c l. Davidson c of near neutral pH was intermediate between the other two soils.

The heavy metals Cd, Co, Cu, Cr, Pb, Ni, Ti, and Zn and B were solubilized and moved into the soil solution and effluent most abundantly by the action of H₂SO₄ on Ava si c l. Because of the very slow rate of flux in the other soils, only a little over one pvd was recovered during several months of treatment. Gypsum crystals appeared at the stalled wetting front in the Nicholson si c.

C. Phosphoric Acid at 6 *N* and 8.8 *N*

A normality of six was selected because the potential acidity is about one third of the normality at pH values below 7. Within a pH range of 3 to 6, only one H⁺ is released by phosphoric acid, thus, a 6 *N* H₃PO₄ solution will have the same acid strength as a 2 *N* HNO₃ solution if the first K dissociation of H₃PO₄ were 10¹. In fact, the K₁ dissociation of H₃PO₄ is only 7.5×10^{-3} . It is evident from the first K dissociation constant of H₃PO₄ that the pH of an H₃PO₄ solution cannot be below 2. Thus, H₃PO₄ is, at least, 100 times weaker in H⁺ ion activity than HNO₃ acid (K₁ diss. 10¹) and at least 10 times weaker than sulfuric acid (K₁ diss. >10⁻¹ and K₂ diss. 12×10^2).

1. Column Flow Characteristics

Phosphoric acid had the slowest wetting front movement of all acids. However, some liquid emerged from the Nicholson si c (one third pvd), unlike the Nicholson treated with H₂SO₄ which did not yield liquid to the 20-cm depth of soil. The flow rates of the other soils from the first 50 ml eluted to the last 50 ml eluted was reduced 5- to 10-fold and finally stopped altogether at about 1 pvd or less (Table 14).

2. pH of Soil Column Effluents

No soil column effluent had a pH below 3.5 during the first pvd, which indicates that considerable neutralization took place preventing the pH from approaching 2.0.

3. Movement of Soil Constituents

Phosphoric acid (6 *N*) moved very slowly through the 20-cm columns of soil and as a consequence provided little data on constituent movement. Although Davidson and Mohave clays yielded very little, if any, heavy metals during the first pvd, Al began moving in fairly large quantities from Davidson c (9800 µg) and modest amounts (235 µg) from Mohave c (Table 14). Iron was not detected in effluents from either soils, not only because of the unfavorable pH for the solution of the oxides, but also due in part to precipitation reactions with the phosphate ions. On the other hand, both Al and Fe were mobilized from the acid Ava si c l. Silica also was much more mobile in the Ava soil than Davidson and Mohave (Ca). Nicholson si c released the largest level of Si (18.1 mg) in the only small amount of

Table 13
THE SOLUBILIZATION AND MOVEMENT OF CONSTITUENTS FROM FOUR SOILS LEACHED
WITH 2 N SULFURIC ACID

Soil constituent ^b	Amount of soil constituent eluted ^a (μg)											
	Mohave (Ca) I				Davidson c				Ava si c I			
	0—0.33	0.33—0.66	0.66—1.00	0—0.33	0.33—0.66	0.66—1.00	0—0.33	0.33—0.66	0—0.33	0.33—0.66	0.66—1.00	
pvd ^c												
B	0.5	0.5	0.5	141	380	500	508	1,022	508	1,022	803	
Cd	0.5	0.5	0.5	0.5	0.5	0.5	62	222	62	222	239	
Co	0.5	0.5	0.5	0.5	2,584	5,824	5,248	6,119	5,248	6,119	2,463	
Cu	123	176	180	74	181	176	2,338	3,914	2,338	3,914	1,985	
Cr	0.5	56	296	0.5	56	296	512	1,605	512	1,605	2,254	
Pb	0.5	192	870	0.5	0.5	0.5	791	1,707	791	1,707	1,930	
Ni	0.5	0.5	0.5	176	608	824	1,634	2,766	1,634	2,766	2,775	
Ti	0.5	0.5	0.5	440	1,216	1,408	2,216	8,298	2,216	8,298	8,540	
Zn	0.5	96	270	80	95	124	16,157	10,268	16,157	10,268	9,397	
Fe × 10 ²	1	1	1	3	6	7	436	3,843	436	3,843	7,111	
Al × 10 ²	3	4	15	97	14,408	29,528	14,208	22,861	14,208	22,861	99,322	
Si × 10 ²	34	39	39	14	113	109	13,349	28,755	13,349	28,755	24,151	
Mn × 10 ²	0.5	7	29	13	3,568	3,461	2,017	1,857	2,017	1,857	683	
Na × 10 ²	17	19	28	80	29	8	717	413	717	413	187	
K × 10 ²	3	3	5	667	389	339	331	30	331	30	13	
Ca × 10 ³	53	65	97	58	39	29	187	77	187	77	58	
Mg × 10 ³	11	13	22	65	41	23	338	212	338	212	268	

^a Nicholson c was wetted by 2 N H₂SO₄ to a depth of 20 cm, but did not yield an effluent flow.

^b Molybdenum concentration was below detectable limits of 50 ppb.

^c One pvd (pore volume displacement) for Mohave soil column = 469 mℓ; for Davidson c = 494 mℓ; for Ava si c I = 489 mℓ; and for Nicholson c = 431 mℓ.

Table 14
THE SOLUBILITY AND MOVEMENT OF CONSTITUENTS FROM FOUR SOILS LEACHED WITH 6 N
PHOSPHORIC ACID

Soil constituent ^b pvd ^c	Amount of soil constituent eluted (μg)										Nicholson ^a silty clay
	Davidson clay		Mohave (Ca) c l		Ava silty clay loam				Nicholson ^a silty clay		
	0—0.33	0.33—0.67	0—0.33	0.33—0.66	0.66—1.0	0—0.33	0.33—0.66	0.66—1.0		1.0—1.1	
B	0.5	0.5	0.5	0.5	60	150	70	0.5	0.5	0.5	0—0.33
P	13,690	594,320	0.5	1,195	488,720	947,567	1,716,800	1,811,160	467,400	14,568	0—0.33
Co	0.2	10	0.2	0.2	84	1,459	2,204	3,142	763	0.2	0—0.33
Cu	0.2	210	16	20	38	697	255	204	21	0.2	0—0.33
Cr	0.2	0.2	0.2	0.2	0.2	95	82	70	10	50	0—0.33
Ni	0.2	537	0.2	16	97	387	1,032	2,727	861	51	0—0.33
Zn	0.2	0.2	0.2	0.2	0.2	907	2,216	1,152	62	0.2	0—0.33
Fe	0.2	0.2	0.2	0.2	0.2	2,130	4,037	1,138	845	0.2	0—0.33
Al	1,100	9,800	78	151	235	176,086	274,920	81,794	340	151	0—0.33
Si × 10 ²	57	311	40	60	188	1,801	1,264	691	74	18,056	0—0.33
Mn × 10 ²	46	76	0.2	0.2	58	804	986	1,097	197	2	0—0.33
Na × 10 ²	42	51	183	222	396	257	982	73	4	251	0—0.33
K × 10 ²	30	45	17	12	18	34	15	12	19	9	0—0.33
Ca × 10 ³	68	342	17	16	32	136	150	106	2	39	0—0.33
Mg × 10 ³	97	49	6	6	16	106	252	647	97	1	0—0.33

^a Nicholson si c was wetted, but stopped yielding effluent after about 1/3 pvd and did not resume flowing.
^b Cd, Mo, Pb, and Ti were not detected in the effluent at concentrations above 0.5 ppm.
^c One pvd (pore volume displacement) for Davidson clay = 494 ml; for Mohave c = 469 ml; for Ava si c l = 489 ml; and Nicholson si c = 431 ml.

effluent (one third pvd) that appeared. The rapid and large mobilization of Si may be responsible, in part at least, for the plugging of the soil. Another possibility is the precipitation of phosphate salts, e.g. CaHPO_4 and Ca_3PO_4 .

Heavy metals, in any sizable amounts, were found almost exclusively in the Ava silty clay effluent. The most prominently mobilized heavy metals were Co, Ni, and Zn, with some lesser amounts of Cu.

The common ions of Ca, Mg, Na, and K appeared in the H_3PO_4 soil-column effluents at relatively modest levels from all soils as compared with HNO_3 and H_2SO_4 effluents.

V. EFFECTS OF STRONG ORGANIC ACIDS ON SOIL

Organic acids, including acetic acid, have been used by industry to enhance the permeability of underground wells, deep disposals, and old encrusted leachate ponds. In addition, acetic acid finds its way into many industrial waste streams as a spent solvent or as a by-product of food processing.

A. Acetic Acid at 2 N

Data was collected for acetic acids on Davidson clay, Nicholson silty clay, Mohave (Ca) silty clay, Ava silty clay, Chalmers silty clay, and Riverbottom sand. Large differences were found, both from element to element and soil to soil as reported below. Data for specific soils is summarized in Figures 2 through 6 (except for the Nicholson).

1. Column Flow Characteristics

The most outstanding characteristic of acetic acid reactions is the fast flow compared with the three inorganic acids at the same $[\text{H}^+]$ ion activity (Table 15). All soils except Nicholson silty clay readily eluted 15 pvd. Acetic acid moved through the coarse-textured Riverbottom sand almost wholly uninhibited, whereas in Nicholson silty clay, acetic acid failed to penetrate down to 20 cm in the column. The slowest flow, ranging from 0.4 to 0.8 cmh^{-1} , occurred through Davidson clay. In Mohave (Ca) silty clay, the flux also started slowly, but elevated to 15 cmh^{-1} before falling back to about 10 cmh^{-1} after 15 pvd. Ava and Chalmers silty clay loams responded similarly to 2 N acetic acid treatment. The flux was more uniform than for the other soils and in the Ava soil averaged about 1 and about 2 cmh^{-1} in the Chalmers silty clay (Table 15).

2. pH of Soil Column Effluent

Except for the calcareous (limey) Mohave (Ca) silty clay, the pH of the soil column effluents rapidly decreased to levels of 3.0 to 4.2 after only 0.5 pvd had taken place. The pH values continued to drop slowly to levels between 2.5 and 2.8 after 15 pvd (Table 15).

3. Movement of Soil Constituents

Al, Fe, Mn, and Si — There appeared to be very little relationship between Al, Si, Fe, and Mn and the rate of movement in the five different soils as a result of acetic acid reactions, Figures 2 through 6. Only Si appeared to reach a consistent rate of movement (170 to 200 $\mu\text{g/g}$) independent of differences in soils. Total amounts solubilized and total movement out of the soil column, however, were a little more variable with different soils as leaching with the acid continued over 8 or more pvd.

Some examples of what may be expected in the variability of Al, Fe, Mn, and Si concentration in the different soil effluents are presented in brief in Table 16. Both high and low values are presented, but it should be noted that the pvd differ somewhat for different soils. The diversity resulted from differences in rate of liquid discharged from each soil. Nevertheless, since maximum concentrations of the element appeared early (i.e., 1 to 5

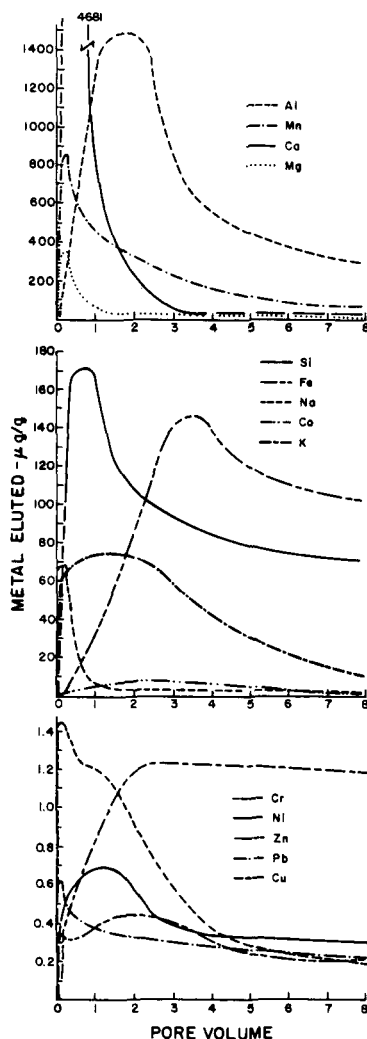


FIGURE 2. The concentration of 12 metals found in 8 pvd of the Davidson soil column effluent receiving 2 *N* acetic acid. (From Fuller, W. H., Artiola, J. F., and Sheets, P., Effect of Hydrogen Ion Concentration of Acid Wastes on Soil Used for Disposal, U.S. EPA CORD Grant No. R807915-01 Rep. U.S. Environmental Protection Agency, Washington, D.C., 1982, 90.)

pvd), the high values will remain the extreme over a range of at least 20 pvd. The low values may be expected to become lower for those not reported to 20 pvd.

Speculation as to how specific mineral forms contribute to the effluents of each soil does not appear to be appropriate at this time. However, at least two soil characteristics emerge as prominent factors influencing solubilization and movement of Al, Fe, Mn, and Si. They are the natural soil pH levels and clay contents under which they formed.

Heavy and trace metals — Only occasionally were the heavy and trace metals found in the soil-column effluents in amounts greater than 2 $\mu\text{g/g}$ during the first pvd. Some metals did not appear in the acetic acid leachates in detectable amounts even after 20 pvd. For example, Cd, Pb, Mo, and Ti of Davidson; Cd, Ti, and Mo of Mohave (Ca); Cd, Ti, and Mo of Ava; Cd, Ti, and Mo of Chalmers; and Cd, Cr, Pb, Ti, and Mo of Riverbottom sand were not present in detectable limits of 0.1 $\mu\text{g/g}$ by the AA method of analysis.

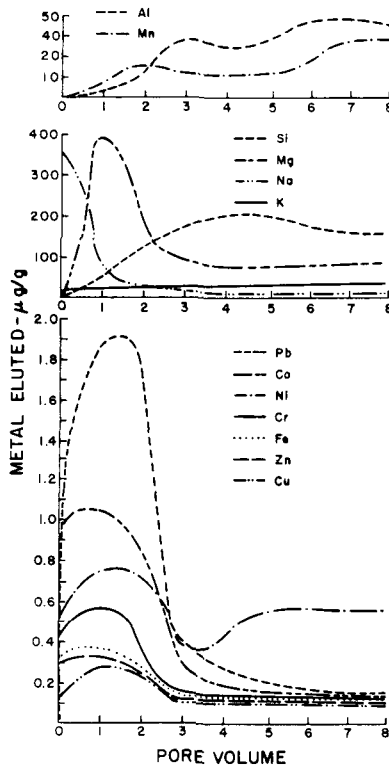


FIGURE 3. The rate of movement of 13 elements during the liquid displacement of 8 PVs from Mohave (Ca) clay loam receiving 2 *N* acetic acid. (From Fuller, W. H., Artiola, J. F., and Sheets, P., Effect of Hydrogen Ion Concentration of Acid Wastes on Soil Used for Disposal, U.S. EPA CORD Grant No. R807915-01 Rep. U.S. Environmental Protection Agency, Washington, D.C., 1982, 90.)

B. Soil Permeability as Influenced by Bulk Density of Soil

Lengthy experience in packing columns of soil verifies that the bulk density can have a significant influence on liquid penetration and flux. Since Nicholson silty clay has had a history of being the most sensitive soil to bulk density change, an experiment was designed to evaluate the effects of loose and firm packing on the penetration of acetic acid through 6.1×20 cm columns. The corresponding bulk densities were 1.54 and 1.46 g/cm³ with column porosities of 0.46 and 0.47.

Acetic acid at 2 *N* completely wetted the 20-cm of Nicholson silty clay in 20 days in the more loosely packed column and caused an expansion of the soil in the column from 20 to 21.5 cm (Figure 7). The more tightly packed column did not become completely wetted. The wetted front extended to a depth of about 12 cm and stopped completely after about 16 days, Figure 7. Movement was not resumed during the next 24 months. The loosely packed Nicholson silty clay maintained a low rate of effluent discharge of about 0.04 to 0.05 cmh⁻¹ during the first 0.25 pvd; thereafter, and until 1 pvd, the rate maintained about 0.09 cmh⁻¹ discharge with a head of about 15 cm.

VI. EFFECTS OF STRONG SPENT-ACID WASTE ON SOIL

This section is concerned with commonly found industrial spent acid wastes and their reactions with soils and, therefore, provides data for comparisons with the reactions of pure

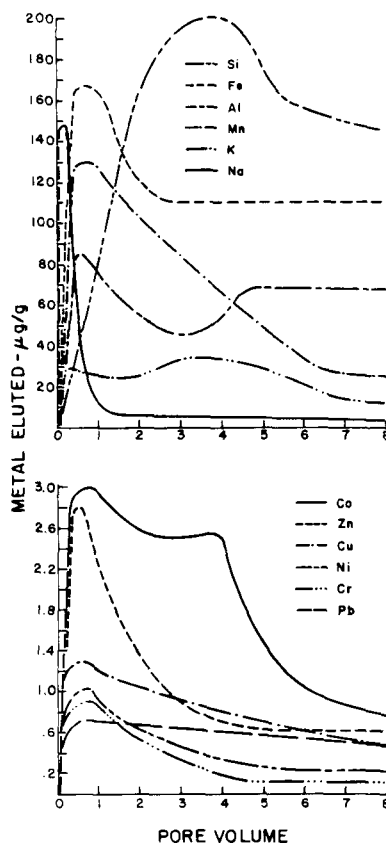


FIGURE 4. The rate of movement of 12 elements during the liquid displacement of 8 pore volumes from Ava silty clay loam receiving 2 *N* acetic acid. (From Fuller, W. H., Artiola, J. F., and Sheets, P., *Effect of Hydrogen Ion Concentration of Acid Wastes on Soil Used for Disposal*, U.S. EPA CORD Grant No. R807915-01 Rep., U.S. Environmental Protection Agency, Washington, D.C., 1982, 90.)

acids just described. All four spent acids, Sylvania™ — spent 2 *N* HNO₃, Wolverine™ — spent 2 *N* HNO₃, Cyprus Bagdad™ — spent 1 *N* H₂SO₄, and Brightening mix — spent 8.8 *N* and 6 *N* H₃PO₄, were not altered from their original composition prior to use.

A. Spent Nitric Acid, 2 *N* — Sylvania™

1. Column Flow Characteristics

The wetting front of the acid migration down the soil column was monitored for each soil (Davidson c, Mohave (Ca) c l, Ava si c l, and Nicholson si c) and the data plotted in Figure 8. The spent nitric acid penetrated Mohave (Ca) c l the fastest, reaching a depth of 20 cm in 7.5 hours. In contrast, the slowest penetration in Nicholson c l required 76 hours. The shape of the permeability curves illustrate a characteristically faster movement of the acid through soils during the initial stages of application that slows considerably as greater depths in the soil were reached and time lapsed (Figure 8). The soil column volume swelled during wetting from the original 20 cm to 21, 21, 20.5, and 23.5 cm for Davidson, Nicholson, Ava, and Mohave (Ca) soils, respectively.

The flow rates of the spent nitric acid, through the porous medium and out of the column as effluent, varied among soils. For example, the flow rates during the first 50 cm of liquid

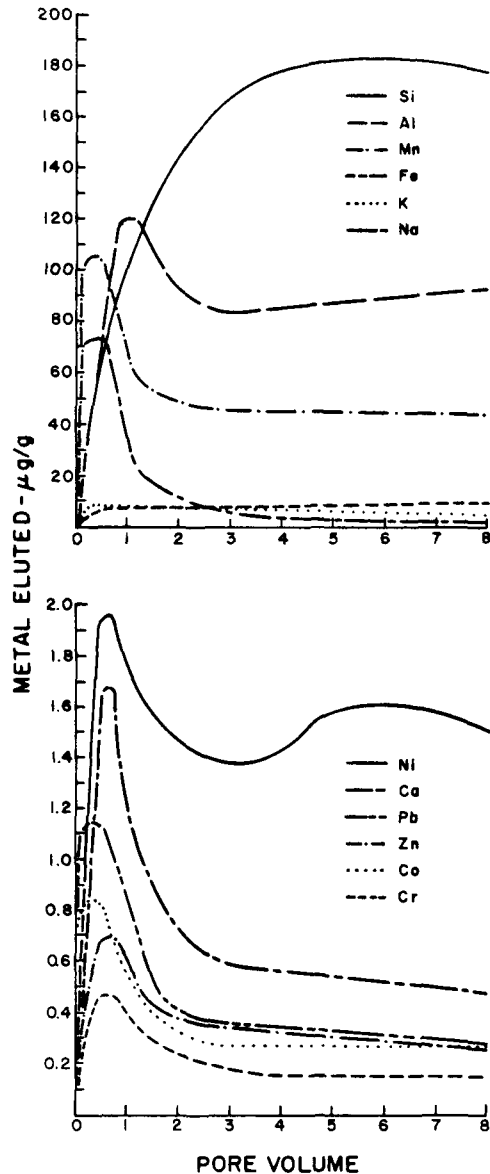


FIGURE 5. The rate of movement of 12 elements during the liquid displacement of 8 pore volumes from Chalmers silty clay loam receiving 2 *N* acetic acid. (From Fuller, W. H., Artiola, J. F., and Sheets, P., Effect of Hydrogen Ion Concentration of Acid Wastes on Soil Used for Disposal, U.S. EPA CORD Grant No. R807915-01 Rep. U.S. Environmental Protection Agency, Washington D.C., 1982, 90.)

eluted was 4.17, 1.67, 1.00, and 0.74 cmh⁻¹ for Mohave (Ca) c l, Davidson c, Ava si c l, and Nicholson si c, respectively. For the same soils in the same order, the last 50 ml of liquid (at 2 pvd) was 2.10, 1.76, 0.56, and 0.54. Davidson clay registered a slight increase in rate of flow during the test period shown. All others registered decreases in flow rates. In general, those soils showing slowest flux (Nicholson and Ava) exhibited the largest variations in effluent volume discharge indicating a progressive erosion and clogging of channels and pore spaces. The increase in flux of Davidson clay, after about the second pvd, is more difficult to explain. Swelling of clays, as indicated by the soil volume change

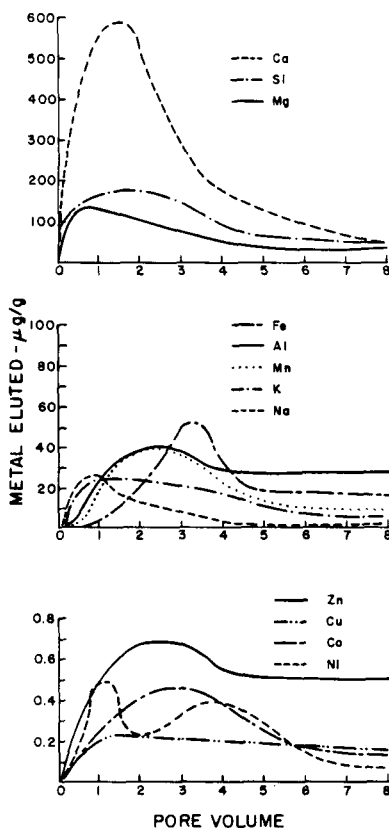


FIGURE 6. The rate of movement of 12 elements during the liquid displacement of 8 pore volumes from riverbottom sand receiving 2 *N* acetic acid. (From Fuller, W. H., Artioli, J. F., and Sheets, P., Effect of Hydrogen Ion Concentration of Acid Wastes on Soil Used for Disposal, U.S. EPA CORD Grant No. R807915-01 Rep. U.S. Environmental Protection Agency, Washington, D.C., 1982, 90.)

during wetting of the spent acid, also must be considered as a factor in flux changes with time.

2. pH of Soil-Column Effluent

The passage of about 1500 mL of spent 2 *N* HNO₃ containing about 2.3% dissolved metals dropped the original soil pH values to as low as 2. The massive levels of H⁺ ions resulted in the solubilization and/or displacement of large amounts of elements such as Al, B, Fe, Mn, Si, Na, K, Ca, and Mg. Other less abundant elements, Cd, Co, Cr, and Ni, also eluted promptly.

3. Movement of Soil Constituents

Iron — Iron did not begin to move from the soil columns until the effluent pH dropped to 3.0. This is expected as Fe activity increases about 1000-fold per unit pH drop in most soil media even though amorphous Fe(OH)₃ controls most of the free Fe in soil solutions and Davidson c and Ava si c l contain about 17 and 4% "free" Fe oxides, respectively. Ava si c l released Fe levels about 10 times higher than Davidson c at pH 2 (Table 17). This indicates that other, less soluble oxide species than amorphous Fe oxides predominate in Davidson soil. Nicholson soil also released large levels of Fe at pH 2 (Iron oxides, 5.6%), but not as high as Ava soil. Mohave (Ca) c l retained its 2.5% Fe oxides the most firmly due to the maintenance of a relatively high pH with "free" carbonates (lime).

Table 15
THE RATE OF FLOW AND pH VALUES OF EFFLUENT FROM FIVE DIFFERENT SOIL COLUMNS
RECEIVING 2 N ACETIC ACID

Measurement	0.1	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4	5	6	7	8	9	10	11	12	15
Pore volume displacement (pvd)																		
Davidson Clay																		
Flow rate (ml/h) ^a	0.40	0.44	0.40	0.45	0.43	0.47	0.77	0.77	0.79	0.73	0.65	0.53	nd ^b	nd	nd	nd	nd	nd
Original soil pH	6.2																	
Effluent pH	4.5	3.7	3.4	3.3	3.4	3.3	3.0	2.9	2.8	2.8	3.0	3.0	nd	nd	nd	nd	nd	nd
Mohave (Ca) Clay Loam																		
Flow rate (ml/h)	0.43	1.35	0.91	0.68	1.45	6.9	14.8	12.9	12.1	12.2	12.0	12.0	11.3	11.0	10.8	10.7	10.7	9.9
Original soil pH	7.8																	
Effluent pH	7.1	6.1	5.8	5.7	4.6	3.7	3.4	3.3	3.2	3.1	3.1	3.2	3.2	3.2	3.2	3.0	3.0	2.7
Ava Silty Clay Loam																		
Flow rate (ml/h)	0.60	0.81	0.97	0.94	0.92	1.0	1.0	1.0	1.0	1.1	1.1	1.1	1.1	1.1	1.2	1.3	1.2	1.3
Original soil pH	4.5																	
Effluent pH	3.9	3.2	3.1	3.0	3.0	3.0	3.2	3.2	3.1	2.9	2.9	2.6	2.5	2.5	2.5	2.8	2.8	2.8
Chalmers Silty Clay Loam																		
Flow rate (ml/h)	0.39	0.81	2.33	2.28	2.39	—	2.32	2.35	2.30	2.09	2.25	2.25	2.26	2.14	2.00	1.72	1.69	2.16
Original soil pH	6.6																	
Effluent pH	6.3	4.2	3.6	3.4	3.4	3.4	3.3	3.3	3.2	3.2	3.2	3.1	3.1	3.1	3.1	3.1	3.0	2.7
Riverbottom Sand: Uninhibited, excessive																		
Flow rate (ml/h)																		
Original soil pH	7.2																	
Effluent pH	nd	3.0	3.0	3.0	3.0	2.9	2.9	2.8	2.8	2.7	2.7	2.8	2.7	2.8	2.8	2.6	2.6	2.5

^a Multiply by 672 to convert to cm/d.
^b nd, not determined.

Table 16
THE HIGH AND LOW CONCENTRATION OF ALUMINUM, IRON,
MANGANESE AND SILICA OF EFFLUENTS FROM FIVE SOILS
RECEIVING 2 N ACETIC ACID ($\mu\text{g/g}$)

Soils	Al		Fe		Mn		Si	
	High	Low	High $\mu\text{g/g}$	Low	High	Low	High	Low
Davidson c (8 pvd) ^a	1500	650	148	108	660	83	170	110
Mohave si c (15 pvd)	38	0.8	0.4	<0.2	31	4.0	220	107
Ava si c l (15 pvd)	410	68	170	100	130	20	200	102
Chalmers si c l (20 pvd)	120	80	0.9	5	0.9	38	270	160
Riverbottom s (20 pvd)	37	19	56	6	44	4	180	30

^a pvd, pore volume displacements represented by the data in the table for the soil indicated.

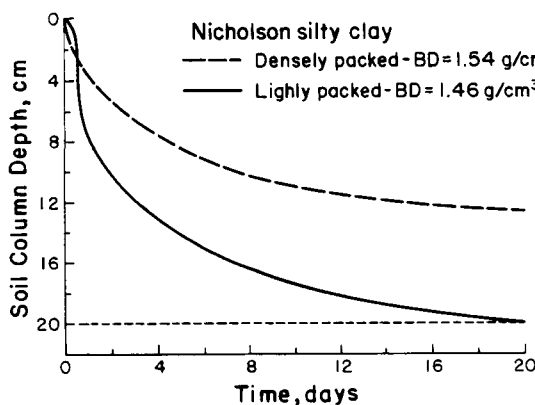


FIGURE 7. The influence of soil packing (bulk density) on the wetted depth of 2 N acetic acid through Nicholson silty clay. (From Fuller, W. H., Artiola, J. F., and Sheets, P., Effect of Hydrogen Ion Concentration of Acid Wastes on Soil Used for Disposal, U.S. EPA CORD Grant R807915-01 Rep. U.S. Environmental Protection Agency, Washington, D.C., 1982, 90.)

Aluminum — Aluminum oxides are several times more soluble than Fe oxides and Al^{+++} began to elute promptly at pH values of 5. Mohave c l did not release significant amounts of Al until after 1 pvd when the pH fell below 5.0. Davidson, Ava, and Nicholson soils released massive amounts of Al throughout the experiment (Table 17). The high release of Al by Davidson soil was due to its high content, about 11%, of the oxides and aluminosilicates compared to the 4 to 6% Al of the other three soils. It should be pointed out that Davidson c is highly weathered containing mostly gibbsite, an aluminosilicate, which controls the Al^{+++} activity.²⁵

Silicon — Silicon activity in soils is also a pH-dependent variable and is controlled mainly by the silicic acid (H_4SiO_4) equilibria. Since this acid is quite insoluble, especially at low pH values, all soils yielded similar Si levels. Silicon levels eluted from Davidson clay were

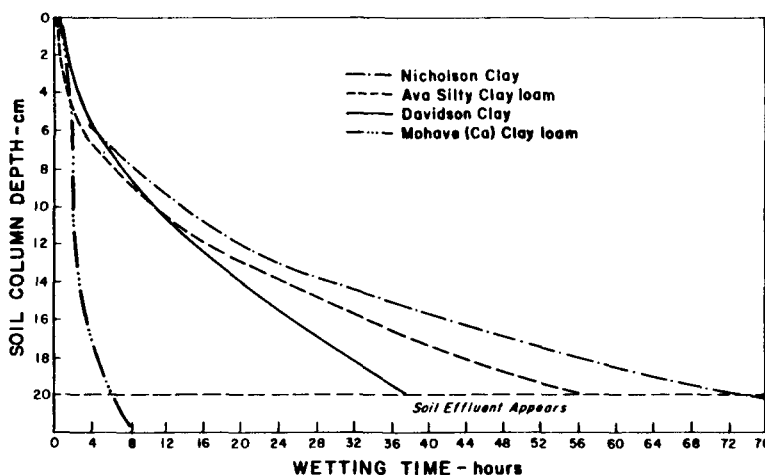


FIGURE 8. The rate of movement of the wetting front of four soils receiving spent 2 *N* nitric acid wastes (Sylvania®). (From Fuller, W. H., Artiola, J. F., and Sheets, P., *Effect of Hydrogen Ion Concentration of Acid Wastes on Soil Used for Disposal*, U.S. EPA CORD Grant No. R807915-01 Rep., U.S. Environmental Protection Agency, Washington, D.C., 1982, 90.)

lower than for the other soils since most silicon-containing minerals in this soil have already been well weathered and leached by natural processes. Most soils showed an increase of Si as the pH dropped due to breakdown of aluminosilicate with the concurrent release of Al by the action of the acid (Table 17).

Manganese — The minerals of Mn, especially the Mn oxides, are very soluble in soils. Because of Mn susceptibility to redox change, it appears in three valence states that control its activity in soils. Mn (II) and Mn (III) are the most important species. The most stable species in soils is Mn (III), which can be identified by a brown-black color. Ava and Nicholson soils showed this characteristic brown coloration in the elutes that contained several hundred micrograms per gram of Mn. However, Davidson and Mohave effluents did not show this color (either light or dark brown) in spite of the fact that they had similar and, in the case of Davidson, higher Mn levels eluting. This may indicate that Davidson and Mohave soils released Mn (II) instead of Mn (III). Colors of eluates for all four soils were carefully noted. Due to the relatively low Mn levels in these soils, except Davidson, signs of Mn solubility exhaustion appeared with each successive pvd. The levels of Mn, particularly in the Mohave c l and Ava si c l effluents, decreased considerably with time (Table 17).

Titanium — Ti is normally found in soils at levels ranging from 0.1 to 1%, although highly weathered soils like Davidson clay may have up to 4% Ti. However, this higher concentration did not affect the levels of Ti in the Davidson soil effluents which showed Ti movement similar to the other three soils (Table 17). In fact, no Ti can positively be attributed to the solubilization of Ti oxides in soils as the acid itself had about 30 µg/g Ti present in solution (a level which closely corresponds to the average in all four soils). Ti minerals are highly insoluble, but apparently can move through soils when in contact with strong acid solutions.

Sodium and potassium — Na and K aluminosilicates are somewhat soluble in soils; however, this would not explain the large levels extracted from the four soils when passing the acid through them. The levels of Na in all eluates decreased with each increment. This would indicate that most of the Na⁺ came from exchange sites (adsorbed Na⁺ displaced by H⁺) and/or from the solubilization of some simple salts present in the soils. On the other

Table 17
THE SOLUBILIZATION AND MOVEMENT OF CONSTITUENTS FROM FOUR SOILS LEACHED WITH SPENT NITRIC ACID WASTE FROM THE PENNSYLVANIA[®] INDUSTRY

Soil constituent ^a	Amount of soil constituent eluted — mg																			
	Davidson clay					Mohave (Ca) clay loam					Ava silty clay loam					Nicholson silty clay				
	0— .5	.5—1	1—1.5	1.5—2		0— .5	.5—1	1—1.5	1.5—2		0— .5	.5—1	1—1.5	1.5—2		0— .5	.5—1	1—1.5	1.5—2	
B	6.7	64	105	96		9.7	33	56	72		22	121	145	133		17	31	53	61	
Cd	0.7	1.0	1.0	0.8		bd ^b	1.5	1.3	0.9		1.3	1.4	1.2	1.1		0.9	1.1	1.1	1.1	
Co	5.7	3.6	3.6	2.8		0.8	4.4	3.1	1.6		7.6	2.1	2.1	1.6		7.5	7.2	5.5	4.9	
Cr	0.6	0.4	0.7	1.0		bd ^b	bd ^b	bd ^b	0.4		2.9	11.0	6.3	5.7		2.2	2.9	3.8	4.0	
Cu	600	707	678	545		0.3	20	185	448		662	777	650	557		456	592	606	544	
Pb	2,680	3,660	3,451	2,744		1.8	4.5	5.9	3.7		1,970	4,639	3,981	3,532		2,610	3,448	3,504	3,170	
Ni	5.0	5.4	5.5	4.7		0.5	9.3	7.8	5.5		8.6	8.4	5.3	5.0		7.9	7.8	6.5	6.0	
Ti	3.9	3.6	3.6	3.7		19.3	22.5	7.2	6.4		4.3	9.3	9.5	13.7		4.2	3.6	3.9	4.1	
Zn	631	636	589	478		4.2	342	559	497		681	1,707	626	295		485	571	571	545	
Fe	0.5	4.5	38	143		bd ^b	0.3	0.4	68		126	4,465	4,049	1,727		385	1,074	1,713	1,891	
Al	5,312	6,232	5,836	4,702		5.1	4.1	368	3,307		4,878	5,343	4,102	3,479		2,301	3,421	3,930	3,881	
Si	12.9	8.1	7.4	6.9		3.8	4.4	4.7	18		16	26	30	26		18	18	20	19	
Mn	253	148	149	104		12.6	131	116	59		288	103	61	45		138	131	90	87	
Na	48	44	52	35		801	615	42	48		82	113	276	164		185	67	67	64	
K	67	71	67	64		58	160	464	576		187	288	406	414		97	159	246	309	
Ca	995	68	55	37		1,130	8,491	5,315	1,506		673	62	57	53		5,504	799	361	256	
Mg	410	72	79	83		694	1,544	1,338	808		853	641	451	377		1,295	720	560	411	

^a Molybdenum concentration was bdl at 0.5 ppm.

^b One pore volume displacement (pvd) for Davidson c = 494 mL; Mohave (Ca) c = 469 mL; Ava si c l = 489 mL, and Nicholson si c = 431 mL

^c bdl, below detectable limits.

hand, the K^+ levels in the effluents increased with time with a concomitant drop in pH, indicating K^+ releases not only from exchange sites, but from entrapped K^+ (phyllosilicates) and also from primary and secondary minerals which dissolved. Effluent Na and K concentrations are very high for Mohave (Ca), Ava, and Nicholson soils, with Davidson c having the lowest amount due to its highly weathered structure. Both of these elements are found at similar levels in soils, with Na minerals being slightly more soluble than K-containing ones. Na salts tend to accumulate more easily than K salt as K^+ is substituted in the formation of secondary minerals.

Calcium and magnesium — Ca minerals, which include silicates, aluminosilicates, carbonates, and oxides, are moderately to very soluble in soils. Furthermore, all of these solubilities are pH dependent; thus, the H^+ activity of nitric acid causes not only Ca-containing minerals to solubilize, but also adsorbed Ca^{++} ions to be displaced. In general, all soils showed a large Ca^{++} release from the very beginning, indicating a major Ca^{++} contribution from carbonates, particularly in soils like Mohave (Ca) c l. This soil released major amounts of Ca^{++} as expected, but so did Nicholson c. However, effluent Ca quickly tapered off in the Nicholson c. Mg carbonates predominate in Mohave (Ca) soil. Nicholson effluent also contains high Mg, but Ava and Davidson soils are both relatively low in Ca and Mg. Magnesium levels showed a similar trend to that of Ca in release from the soils, except for Mohave (Ca) soil which showed an increase in Mg output with increasing effluent discharge (Table 17.) The effluent Mg levels also showed less of a steep decline with time from other soils when compared with that of Ca. Magnesium carbonate reacts more slowly to cold acids than calcium carbonate. Other Ca and Mg minerals are similar in overall solubilities, except for the sulfates, which are relatively soluble for Mg and relatively insoluble for Ca. The contributions of Ca and Mg to the eluates are most likely controlled by adsorbed ions in the case of Mg and the dissolution of carbonates and oxides in the case of Ca.

Boron — Boron is present in the spent nitric acid used in this study at a level of about 600 $\mu\text{g/g}$. Naturally occurring B containing minerals are extremely insoluble. Thus, no soil contributions should be expected, at least in the short time span involved. Boron, probably as boric acid, migrated very quickly through the soils used and at higher rates with decreasing pH (Table 17). Mohave (Ca) c l retained B better than Ava si c l. The retention of B was poor in Ava soil, although the reasons are not clear, since B (as boric acid) solubility decreases with decreasing pH. The B movement through the four soils used is not easily explained. The total B levels in each of these soils does little to explain these results, as both Mohave (Ca) c l and Nicholson si c seem to have more natural B than either Davidson or Ava soils, yet they slowed the migration of B more readily.

Chromium, cobalt, nickel, cadmium, and molybdenum — Heavy metal elements are present in the spent acid at levels below 10 $\mu\text{g/g}$ (Table 17). The soils themselves also contain small amounts of these metals. Chromium is shown to elute at levels much higher than those contained in the acid. Thus, the soils are contributing. Only Mohave (Ca) c l contained Cr at the level found in the HNO_3 , due to the pH. This indicates that Cr^{3+} is present in the acid rather than Cr^{6+} . Co is contained in trace amounts ($<1 \mu\text{g/g}$) in the HNO_3 and at levels below 70 $\mu\text{g/g}$ in the four soils used in this study. The soils contributed relatively large amounts of Co, especially Nicholson, Ava, and Mohave. A similar pattern arises in Ni migration through these soils, with contributions above and beyond that present in the acid alone, especially early on. Cadmium levels also reached the spent H_2NO_3 levels quickly, and in some cases slightly higher values are reported. Since total soil Cd is so small, it is difficult to predict whether or not the soils are the origin. Molybdenum did not appear in the soil effluents at levels above 1 $\mu\text{g/g}$ at any time. It appears that the soil contributions of these heavy metals come mainly from some metal oxides and sulfates present in the soil minerals rather than from exchanged sites, since their elution levels increase with decreasing pH.

Zinc, copper, and lead — The migration of these three metals through Ava, Davidson, Nicholson, and Mohave soils was nearly complete once the elutes pH dropped below 5. In all cases the metal output was equal to the input within the first two pvd (Table 17). These metals were contained in the spent nitric acids at levels in the thousand micrograms per gram range. But, the main cause for the massive migration was the high H^+ concentration ($2\ N\ HNO_3$) of the spent acid that saturated all exchange sites in the soils, while also preventing these metals which are pH dependent from precipitating. Mohave soil was effective in delaying the movement of these three metals for about 1 pvd due to its large buffering capacity which kept the soil pH above 6. However, the Mohave presented a problem related to its tendency to give off CO_2 from the dissolution of carbonates after acid addition. Disturbances resulted from gas formation with the development of bubbles and large channels through the profile. Davidson, Nicholson, and Ava soils were unsuccessful in retaining any of these metals. Because of the small amounts of these metals present in the natural soil, it is difficult to detect any significant contribution from the soils in the eluates (Table 17).

B. Spent Nitric Acid 2 N — Wolverine™

The composition of spent nitric acid waste from Wolverine™ is similar to that of Sylvania™ wastes, considering the usual wide variations found in industrial spent acid waste streams. Specifically, it is lower in Pb, higher in Cu, and contains substantially more Ti and Zr than Sylvania™ nitric acid (Table 2). Its reaction with the four soils, Davidson clay, Nicholson silty clay, Ava silty clay loam, and Riverbottom sand, was similar to that of the Sylvania™ spent nitric acid, yet subtle differences were found that will be discussed briefly.

1. Column Flow Characteristics

The four soils were less permeable to the spent nitric acid from the Wolverine™ source than from Sylvania™ (Table 18). Other than the differences between the two sources reported above, only the titratable acidity was higher in the Wolverine™. The nitrate-N concentration was about the same in both. A tendency was found for the flow rate to decrease with time in all soils except for a short period in Ava silty clay. Crust development at the air-liquid surface was more difficult to control in the Wolverine™ columns than in the Sylvania™. The very slow rate of flux of the spent acid delayed data collection, and eventually, after about 3 pvd for all soils (except Riverbottom sand), effluent flow dropped to near zero. After 4 pvd Ava silty clay flux also decreased to near zero.

2. pH of Soil Column Effluent

The pH values of the Wolverine™ effluents were similar to those of Sylvania™. The pH dropped rapidly in the effluent from all soils to between 3 and 4 in less than 1 pvd. As the pH values of the solution bathing the soil decreased, the solubility and movement of metals out of the soil column increased substantially (Table 18).

3. Movement of Soil Constituents

All constituents moved easily from the four soils. Because of the low clay content and consequent poor buffering capacity of river sand, the native carbonates were rapidly decomposed by the overwhelming H^+ activity of the spent nitric acid and the soluble metal salts of nitrate moved out of the soil into the effluent at relatively high concentrations (Table 18). Those soluble metals contained in the spent nitric acid appeared at high levels (i.e., about the same concentration of the influent) within the first 0.5 pvd.

Copper at 26,700 $\mu g/g$ in the spent acid, for example, was poorly retained by all soils and appeared immediately in the effluent, as did Pb, Ti, and Zr. The Fe, Al, and Cd was somewhat retained during the first 0.5 pvd. Breakthrough ($c/c_0 = 1$), however, usually occurred for these elements as well as others after 1 or 2 pvd.

Table 18
THE MOVEMENT OF COMBINED CONSTITUENTS FROM SOIL AND SPENT WOLVERINE®
2 N NITRIC ACID THROUGH FOUR SOILS

Constituent pvd →	Amount of constituent eluted (mg)							
	Davidson clay				Nicholson clay loam			
	0—0.5	0.5—1.0	1.0—1.5	1.5—2.0	0—0.25	0.25—0.50	0.5—1.0	1.0—2.0
Flux-m ² /hr ^a	0.71	0.57	0.46	0.40	0.17	0.11	0.12	
pH	6.8—4.5	4.5—3.2	3.2—3.0	3.0—2.6	6.7—6.0	6.0—4.8	4.8—3.2	
Cd	0.7	1.1	0.6	0.7	0.3	0.4	1.0	nd ^b
Co	5	12.5	0.9	1.4	1.4	0.9	2.4	
Cr	2	2	0.6	0.6	0.9	1.7	4.4	
Cu	4.8	17.1	23.9	26.7	10.5	17.0	35.4	
Ni	0.2	0.7	8.1	22.0	4.4	6.4	13.3	
Mn	235	120	120	195	195	69	36.1	
Pb	3.4	16	1,722	1,795	770	1,216	2,251	
Si	1.3	1.0	2.9	6.6	2.4	2.6	5.8	
Ti	24	10	11	9	10.0	8.1	7.2	
Zn	7.8	21.4	188	125	88	144	317	
Al	3,522	1,904	1,491	2,382	1,434	27,825	577	
Fe	19	18	14	1,047	213	713	2,425	
Na	49	45	23	25	68	41	56	
K	71	67	53	155	29	81	101	
Ca	210	116	43	92	1,900	345	433	
Mg	352	125	85	89	507	497	768	
pvd	Ava silty clay loam				Riverbottom sand			
	0—0.5	0.5—1.0	1.0—1.5	1.5—2.0	0—0.5	0.5—1.0	1.0—2.0	2.0—3.0
	0.17	0.16	0.21	0.26	53	24	24	17
Flux-m ² /hr	4.5—3.2	3.2—3.0	3.0—2.9	2.9—2.4	7.2—4.2	4.2—3.0	3.0—2.8	2.8—2.6
pH								

Flux-ml/hr	0.17	0.16	0.21	0.26	53	24	24	17
pH	4.5—3.2	3.2—3.0	3.0—2.9	2.9—2.4	7.2—4.2	4.2—3.0	3.0—2.8	2.8—2.6
B	32	142	142	131	25	110	28	21
Cd	0.7	0.7	0.7	0.6	0.7	0.7	0.8	0.8
Cr	1.7	2.0	1.7	3.3	2.1	2.0	2.1	2.6
Cu	21	22	22	25	1,450	1,300	3,200	3,700
Ni	8.8	7.5	7.6	7.6	8	11	11	11
Mn	53	305	72	4.2	23	84	43	22
Pb	1,573	1,546	1,725	1,732	2,258	2,066	2,279	2,584
Si	2.1	3.9	4.0	5.4	9.5	7.2	8.1	8.0
Ti	101	122	121	121	246	242	246	242
Zn	104	96	163	175	307	315	320	271
Al	3,961	3,864	3,947	3,588	572	2,170	2,111	2,450
Fe	373	2,843	2,995	2,900	25	942	2,705	3,053
Na	43	112	255	326	521	126	87	144
K	118	243	559	698	892	851	839	1,257
Ca	471	100	127	130	nd	2,466	1,385	394
Mg	529	422	317	317	1,220	1,133	1,521	1,461

^a Multiply by 672 to convert to cm/d.

^b nd, not determined.

The failure of the soil to function in a capacity of attenuation and/or as a barrier is evidenced by the mineral-decomposition metals appearing in the effluent. All of the basic constituents, Na, K, Ca, and Mg, the Al, Fe, Mn, and Si, and many of the heavy metals, Co, Cr, Ni, and Zn, appear in the effluent in higher concentrations than applied as influent (Table 18).

C. Spent Sulfuric Acid 1 N — Cyprus-Bagdad™

Spent sulfuric acid at 1 N was obtained as mentioned from the Cyprus-Bagdad Copper Mine of Bagdad, Ariz. The composition of the waste acid varies from time-to-time depending on many factors among which are

1. Nature of the ore being processed
2. Load relations of the acid
3. Capacity of the operations
4. Even the time of day

The spent acid used for these experiments as reported in Table 2 is quite representative of the usual waste stream. The metals occurring in the liquid sulfuric acid waste in concentration of 1000 ppm or over are Al, Cd, Cu, and Fe. Mn content is 234 ppm. Five soils, Nicholson si c, Ava si c l, Mohave (Ca) c l, Anthony s l, and Riverbottom sand were used along with a mined natural secondary clay mineral (smectite, 99% pure) from the vicinity of Bagdad, Arizona.

1. Column Flow Characteristics

The different air-dry soils wetted quite differently by the spent H_2SO_4 , depending primarily on their texture. For example, the length of time to wet the soils ranged from 3, 4, 16, 64, 65, and 318 hours for Riverbottom sand, Anthony sandy loam, Ava silty clay loam, Mohave clay loam, smectite clay, and Nicholson clay loam, respectively. The spent sulfuric acid flow characteristics varied similarly, as it took 24, 30, 150, 158, 288, and 1056 hours to collect the first 50 mℓ of effluent from the same respective soils. Flow through Nicholson si c and the smectite clay stopped to 0 after 4 months of treatment and the columns had to be abandoned. Only Riverbottom sand, Ava si c l, and Anthony dripped effluent after 4 months, but only Riberbottom sand yielded easily measurable effluent.

2. pH of Soil Column Effluent

The effect of the spent copper mine acid was one of quickly overcoming the natural buffering capacity, clay adsorption, and carbonate neutralization of the soils (Table 19). The naturally acid Ava si c l was not capable of maintaining its aqueous pH. The carbonate-containing soils, Mohave (Ca) and Riverbottom sand, or the clay soils, Nicholson and smectite, also emitted very acid effluents in a short period of time. As the pH decreased, the electrical conductivity increased, and soluble salts moved abundantly from the soil (Figure 9).

3. Movement of Soil Constituents

The movement of soil constituents through Nicholson silty clay, Mohave clay loam, and smectite clay ceased when flow stopped after about 1 to 2 pvd. The total volume of effluent accumulated in 120 days was 159, 296, 497, 1700, 1820, and 4050 mℓ for Nicholson c l, Davidson c, smectite, Anthony s l, Ava si c l, and Riverbottom sand, respectively. The capacity of the 20 cm of soil to function as a barrier to metal pollutant movement, therefore, was not attenuation, but blocking of liquid flow due to plugging and clogging of the soil-transport channels and pores. The Ava silty clay loam and Riverbottom sand illustrate what

Table 19

THE MOVEMENT OF COMBINED CONSTITUENTS FROM SOIL AND SPENT SULFURIC ACID
(1 N) WASTE STREAM THROUGH FIVE SOILS AND NATURAL SMECTITE CLAY
(CYPRUS-BAGDAD)

Analyses		Amount of constituent eluted— μg											
		Nicholson si c			Mohave (Ca) c l			Smectite clay			Anthony s l		
		0—0.25	0.25—0.5		0—0.5	0.5—1.0		0—0.5	0.5—1.0		0—1	1—2	2—3
Flux— ml/h^a	pvd	0.08—0.1	0.1—0.1	0.83—1.33	1.33—0.79	0.04—0.5	0.5—0.04	11—6.0	6.0—4.3	4.3—4.0			
E. Cond.— mmhos/cm		1.25	2.86	3.25	4.20	4.00	3.10	5.20	28.85	31.10			
pH		6.3	6.3	7.6	6.5	7.8	6.5	7.1	6.1	6.0			
Co		bdl	bdl	bdl	bdl	bdl	bdl	2,520	7,630	6,700			
Cu		bdl	bdl	bdl	bdl	bdl	bdl	133	55,200	320,320			
Ni		bdl	bdl	bdl	bdl	bdl	bdl	3,420	6,530	5,400			
Zn		bdl	bdl	bdl	bdl	bdl	bdl	bdl	25,600	26,500			
Mn		3,975	8,162	674	1,049	72	bdl	76,000	143,680	120,920			
Fe		bdl	bdl	bdl	bdl	bdl	bdl	120	130	118			
Na		4,080	10,810	55,300	46,320	17,027	13,610	88,400	84,860	85,750			
K		178	339	4,770	2,075	4,180	1,395	18,360	32,400	35,360			
Ca		9,170	20,990	32,153	280,740	182,570	$1,243 \times 10^3$	412,060	307,200	277,900			
Mg		1,431	3,690	23,250	32,950	31,430	32,163	nd	nd	nd			

Analyses		Ava si c l						Riverbottom sand					
		0—1			1—2			0—1			1—2		
		0—1	1—2	2—3	3—4			0—1	1—2	2—3	3—4		
Flux— ml/h	pvd	5.5—3.2	3.2—2.8	2.8—1.67	1.67—0.83	1.30—2.55	2.55—16.0	16—8.3	8.3—4.4				
E. Cond.— mmhos/cm		5.85	20.20	12.00	19.00	4.10	14.00	28.10	31.00				
pH		4.2	3.5	3.5	3.4	7.3	6.8	6.4	5.0				
Cd		bdl	48	850	860	bdl	bdl	bdl	441				
Co		8,370	7,770	156	160	bdl	195	5,880	6,468				
Cr		bdl	bdl	175	520	bdl	bdl	bdl	152				
Cu		245,640	315,150	382,260	386,400	bdl	117	5,590	414,460				

Table 19 (continued)
THE MOVEMENT OF COMBINED CONSTITUENTS FROM SOIL AND SPENT SULFURIC ACID
(1 N) WASTE STREAM THROUGH FIVE SOILS AND NATURAL SMECTITE CLAY
(CYPRUS-BAGDAD)

	Ava si c l				Riverbottom sand			
	0—1	1—2	2—3	3—4	0—1	1—2	2—3	3—4
pvd								
Pb	bd ^a	1,700	1,800	1,900	bd ^a	bd ^a	bd ^a	bd ^a
Ni	5,900	6,300	5,200	4,600	bd ^a	2,590	5,090	5,090
Zn	24,600	23,640	23,800	18,800	bd ^a	7,644	19,600	24,300
Fe	2,500	2,300	4,200	33,850	bd ^a	bd ^a	bd ^a	110
Al	1,420	2,160	5,600	5,010	nd	nd	nd	nd
Si	38	210	251	800	bd ^a	270	3,200	3,200
Mn	230,900	136,600	132,900	102,600	bd ^a	180	89,380	116,420
Na	101,660	90,600	131,160	100,700	28,100	36,850	132,500	74,500
K	53,800	48,300	60,300	60,300	124,660	15,290	42,730	38,020
Ca	310,500	25,680	221,260	203,320	716,600	278,710	346,140	228,930
Mg	713,000	$1,377 \times 10^3$	$1,083 \times 10^3$	977×10^3	750,100	10.2×10^5	13.4×10^5	9.8×10^5

Note: This spent H_2SO_4 originated from Cyprus-Bagdad Copper Mine, Bagdad, Ariz.

^a Multiply by 672 to convert to cm/d.

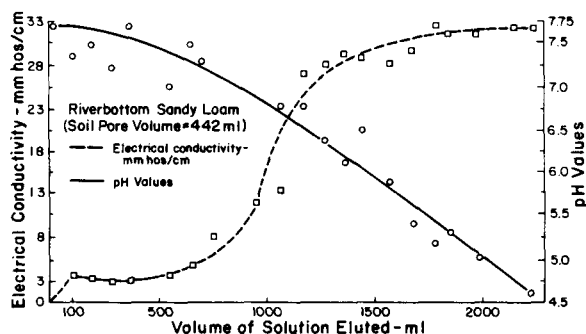


FIGURE 9. Influence of spent sulfuric acid (Cyprus-Bagdad Copper Mines) waste passed through riverbottom sand on the pH and electrical conductivity (salts) of the soil solution eluted from 36-cm column of soil. (From Fuller, W. H., Artiola, J. F., and Sheets, P., Effect of Hydrogen Ion Concentration of Acid Wastes on Soil used for Disposal, U.S. EPA CORD Grant No. R807915-01 Rep., U.S. Environmental Protection Agency, Washington, D.C., 1982, 90.)

can be expected when soil flux is maintained. Relatively large concentrations of most metals were solubilized and moved through the soil and out of the column into the effluents.

Copper, nickel, and zinc — The Cu, Ni, and Zn movement appears to be highly pH dependent. These metals did not appear in the first pvd in any of the slowly flowing Nicholson silt, Mohave clay, or smectite (Table 18) tests, despite concentrations of up to 1083 $\mu\text{g/g}$ in the spent acid influent. On the other hand, Cu showed in the first pvd of the acid Ava soil and the sandy Anthony. The presence of small amounts of free limestone in the Riverbottom sand accounted for the retention of Cu as a carbonate during the first pvd. Although Anthony silt has a higher pH than Riverbottom sand (7.8 as opposed to 7.2), it has no free limestone or lime and this may, therefore, account for the 133 μg Cu per gram of Cu appearing in the first pvd as compared with none for river sand. Nickel and Zn behaved in the five soils and smectite similarly to that of Cu.

Iron, aluminum, and silicon — The amount of Fe and Al in the spent H_2SO_4 was relatively high, being 1660 and 2340 $\mu\text{g/g}$, respectively. Fe moved more freely than Al in the acid Ava soil and appeared in the effluent of the alkaline Anthony silt even at pH levels from neutral to 6.0 (Table 19), although it was slow to move in the Riverbottom sand until a pH of about 5.0 developed. Silica, on the other hand, moved out of Ava silt more slowly than the river sand where it reached a concentration of 3200 μg in the second to third pvd. Silica is less influenced by the low pH values 4 to 3 of the Ava soil than Fe and Al. Since the original spent H_2SO_4 contained only 212 $\mu\text{g/g}$ of Si, the Riverbottom sand contributed substantial amounts to the soil solution and effluent just as Ava soil contributed to the Fe and Al eluted.

Manganese — Mn is very susceptible to hydrogen ion activity and redox changes. All soils contributed freely to the pool of soluble Mn. Over 143,000 μg of Mn was solubilized in the second pvd of the Anthony silt and moved into the effluent from the 20-cm column of soil. Values over 100,000 μg moved through Anthony, Ava, and Riverbottom soils.

Cadmium, cobalt, chromium, and lead — The four hazardous metal pollutants Cd, Co, Cr, and Pb were mobile in Ava silt and were identified in abundance in the effluents. The spent acid was well supplied with Cd (1000 $\mu\text{g/g}$) (Table 2) and was found in the effluents at about 860 $\mu\text{g/g}$. Co exhibited just the opposite behavior. Only 17 $\mu\text{g/g}$ was present in the influent and up to 8000 μg eluted in the effluent of the first pvd of Ava silt, and between 2500 and 7600 μg was solubilized from the Anthony silt during the three pvd

reported (Table 19). Two soils, Nicholson silty clay and Mohave (California) clay, and smectite clay yielded none of these four metals to effluent during the first pvd. Cadmium, Cr, and Pb were below detectable limits ($0.05 \mu\text{g/g}$) in the third pvd of Anthony silty clay. The Cr that eluted from Ava and Riverbottom soils had to originate from the soil itself as a result of the action of spent H_2SO_4 since only about 1 ppm was contained in the influent. The $540 \mu\text{g}$ mobilized from the third pvd of Ava silty clay represents a substantial leakage from natural soil and even the $150 \mu\text{g}$ from river sand must be considered a failure of the soil as a barrier to such a potentially hazardous metal as Cr.

Sodium, potassium, calcium, and magnesium — Just as with the other strong mineral acids, the alkaline and alkali earth metals were very mobile and moved into the soil column effluent without obvious restriction.

D. Spent Phosphoric Acid 8.8 N and 6 N — Brightening Mix

The spent phosphoric acid was a mixture of five H_3PO_4 wastes derived from several industrial sources as a residue from brightening processes of automobile parts. It represented solutions collected for ammonium neutralization in preparation for use as agricultural fertilizers. The original waste was calculated to be 8.8 N H_3PO_4 . Studies included the original waste and a 6 N waste, diluted for comparative purposes and to more readily penetrate the 20-cm of study soils. It is characterized as containing high levels of Al and P only and low levels of heavy metals, Cd, Cu, Cr, Fe, Pb, Ni, and Zn.

1. Column Flow Characteristics

The spent phosphoric acid (H_3PO_4) waste at a normality of 8.8 did not penetrate the 20 cm of Davidson clay, Nicholson silty clay, or Ava silty clay loam. However, this original waste flowed slowly through Riverbottom sand (Table 20). The 8.8 N H_3PO_4 moved somewhat more readily through the soils when diluted to 6 N but here again after only 0.4 and 0.07 pvd flow stopped completely in Davidson and Ava soils, respectively. Flow did not resume, at least not for 2 years.

2. pH of Soil Column Effluent

The pH of the soil-column effluent dropped rapidly from that of the original water-saturation level to between 3.4 and 3.2 during the elution of the first 0.5 pvd. After about 1.5 pvd the pH of the Riverbottom sand dropped to pH 2.8 (Table 20).

3. Movement of Soil Constituents and Spent Acid Metals

The movement of metals from all sources through Davidson clay, Ava silty clay loam, and Nicholson clay was very limited, being confined to the action of the 6N H_3PO_4 only. The movement through river sand, however, was not seriously restricted up to about 3 pvd (Table 20). The river sand was very porous and contained only about 1% clay.

Phosphate leaked freely from Riverbottom sand. Manganese, Al, and Fe along with Si were solubilized by the action of H_3PO_4 on soil. Attenuation was very limited if at all present. The source of heavy metals in the Riverbottom sand effluent originated primarily from the soil since the spent acid was relatively low in these metals (Cd, Cu, Cr, Ni, Pb, Ti, and Zn). Compare data from Table 2 with that in Table 20.

VII. DISCUSSION

Any one or all of the three main components of waste disposal on land, the soil, the vehicle of transport, and a potential pollutant within the transport vehicle, may contribute to unacceptable environmental pollution. The behavior of these components as affected by the kind of acid and $[\text{H}]^+$ ion strength, both pure and contaminated with metals, have been

Table 20
THE MOVEMENT OF CONSTITUENTS FROM SOIL COLUMNS RECEIVING PHOSPHORIC ACID
WASTE MIX AT 8.8 N AND 6.0 N

Constituent pvd ^a	Davidson c 6 N H ₃ PO ₄ 0.40	Ava si c l 6 N H ₃ PO ₄ 0.07	Amount of constituent eluted—µg					
			8.8 N H ₃ PO ₄			Riverbottom sand		
			0—0.5	.5—1.0	1.0—1.5	1.5—2.0	0—0.5	0.5—1.0
Flux—m ³ /hr ^d	0.039—0	0.014—0	53	46	42	42	71	46
pH	5.3	3.4	5.1	3.2	3.2	3.0	5.2	3.3
P × 10 ³	170,500	98,000	190,900	171,000	176,000	292,000	82,000	175,000
Cd	96		7	5	1,443	3,122	6	2,033
Co	73		122	405	1,450	1,550	203	1,178
Cr	180		bd ^b	bdl	82	1,980	bdl	101
Cu	4		5,957	7,009	122	201	4,007	65
Ni	30		500	754	1,332	4,014	428	845
Mn	16,100		11,666	21,600	26,000	83,500	19,822	19,320
Pb	13		251	269	114	268	361	270
Si	260		750	982	2,553	3,568	2,550	26,650
Ti	<2		bdl	250	1,776	10,927	bdl	3,000
Zn	54		1,283	2,203	2,155	8,474	1,367	278
Al × 10 ³	34		82	98	1,432	2,408	913	1,005
Fe × 10 ³	88		700	2,500	147	963	6,500	17,980
Nia × 10 ²	19		nd ^c	nd	117	245	nd	92
K × 10 ²	18		nd	nd	90	457	nd	133
Ca × 10 ³	72		nd	nd	204	314	nd	215
Mg × 10 ³	22	19 ml of effluent, insufficient for analysis	nd	nd	112	1,204	nd	104

^a The pore volume for Davidson c, Ava si c l and Riverbottom sand are 275, 271, and 213, respectively.
^b bdl, below detectable limits.
^c nd, not determined.
^d Multiply by 672 to convert to cm/d.

compared. We now address each of these main components as generally related to acid-waste disposal on land.

A. The Soil

1. Natural Soil Constituents

Total chemical analyses of soils reveal the presence of an abundance of elements, Al, Si, Fe, Ca, Mg, Na, and K in mineral forms (Table 1). Anion and anion-forming elements, C, N, P, and O are prominent in soils. Less abundant are Cd, Co, Cr, Cu, Mo, Pb, Se, Ti, and Zn. In fact, most elements of the earth's crust appear in some mineral form in soil, while others are adsorbed on exchange sites or are found in salts.^{26,27} The solubility of most of the primary and secondary minerals by aqueous solution is relatively low, often below detectable limits for some elements as determined by the most commonly used AA equipment. Other elements of relatively low molecular weight (C, O, N, P, S, Ca, Mg, Na, and K, for example) are found in detectable amounts in the natural soil solution and organic matter. Plant nutrients frequently dominate the soluble salts in such dilute aqueous solutions.

Comparing the effects of the more dilute (weaker) solutions together, it was found that relatively small amounts of Ca, Mg, Na, K, Si, P, N, S, and Cl are represented in aqueous effluents of most soils. Leaching with pure water did not release potentially hazardous metals from any soils in measurable or significant amounts. Solubilization and movement of some metals in soils is a continuing process, but usually very small. The total content of any one element in the soil is not a reliable guide as to what may be expected to be found (1) in the soil solution, (2) in pure water or, (3) in MSW leachates.

The municipal solid waste landfill-type leachate contributed little more pollution to the soil-column effluent than pure water during the 15 to 20 pvd study. Since the soil was capable of attenuating the low levels of potentially hazardous metals of MSW leachates, only minimum attention need be given such leachates if the soil layers beneath and surrounding the landfills are deep and fine textured. If, however, industrial disposals of pollutants become associated with MSW landfills, the presence of salts and organic constituents can contribute to enhanced migration rates and special monitoring and management practices are required.

Certain soil properties stand out as being more closely correlated with attenuation and mobility of metals than others. For dilute aqueous solutions, such as MSW leachate, Korte et al. found significant correlation between mass adsorption or attenuation and six soil parameters: clay, pH, cation exchange capacity, surface area, Fe_2O_3 , and Mn. Although soil pH did not appear to provide additional significance to the correlations with some metals, it helped others such as Cr and Se.

2. Soil pH

These same soil properties, as listed above, influence the rate of attenuation or movement of metals through soils receiving dilute and strong acids and spent acid wastes. With acid wastes, the pH of the soil assumed a much greater role in the rate and extent of metal movement. *Ava si c l*, for example, has a naturally low pH of 4.5, and almost all metals escaped sooner and in greater concentrations than soils of near neutral pH. This was due in part to the original low pH as well as to the lesser volume of acid waste necessary to bring the soil pH to a critical pH of about 3 for metals. For the soil within the near neutral to alkaline range, a pH of about 5 appeared to be another critical pH reference level for metal movement acceleration. However, certain elements such as Si did not respond as dramatically to the lowering of the pH.

3. Soil Texture

The clay (<0.002 mm) content influences retention of soluble metals regardless of origin

as a result of a larger surface area, higher buffering capacity, and adsorption which delays the appearance of soil constituents in the effluent. When strong acids were involved, however, the delay was temporary and short-lived. Clogging and plugging was also most prominently associated with clay content of soils, primarily due to the smaller pore and channel diameters rather than to coarse textured soils.

4. Lime Content

Another soil factor influencing the solubility of constituents and subsequent movement is the presence of lime. Mohave (Ca) clay loam retained the soil constituents against failure longer than other soils of similar composition not containing “free” carbonates.

5. Specific Mineral Species and Salts

Some soils contained more acid-soluble minerals than others. Thus, individual soils differ due to differences in specific constituent composition. Davidson clay, for example, is abundantly supplied with Mn which is reflected in the relatively high Mn of the effluent. Cobalt in Davidson clay also shows the same tendency to become soluble. Soluble salts such as those found in arid-zone soils also have specific characteristics that contribute to soil solution composition.

B. The Vehicle of Transport

1. Factors Affecting Constituent Solubility and Soil Permeability

Attenuation of metals contained in strictly MSW landfill leachates and water are influenced primarily by such prominent solution characteristics as:^{24,26,27}

1. Total organic carbon compounds (TOC)
2. Total soluble salts (or dissolved solids)
3. Acidity or alkalinity
4. Potential pollutant concentration

These characteristics along with those for soil were incorporated into a mathematical model, and specific equations were developed for predicting attenuation or movement of Cd, Cr, Ni, and Zn through soils,²⁸⁻³¹ as demonstrated in Chapter 4. The relationships as developed are useful only with aqueous waste streams at pH values from about 5 to 7.8. New equations are needed for strong acids, yet, some of the same transport solution characteristics listed remain relevant for acid media. Additional characteristics are now identified which have serious impact on solubility, concentration, and movement of potential pollutants whether originating from the soil or the spent acid wastes. Some of these are

1. Concentration of the acid (H^+ ion mass)
2. Potential pollutant in spent acid (Cu, Pb, Al)
3. Reduction/oxidation properties
4. Kind of acid (H_2NO_3 , H_2SO_4 , H_3PO_4 , acetic)

2. Concentration Effects of the Acids

Several good examples of the effects of waste acid concentration on solubilization, concentration, and movement of soil constituents have been described in this chapter. In the sulfuric acid series, compare water at pH 7.0 (Table 5), H_2SO_4 at pH 3.0 (Table 6), pure H_2SO_4 at 2 N (Table 13), and spent H_2SO_4 at 1 N (Table 19) in any given soil. The amount of soluble metals in the effluent follows the order: spent 1 N H_2SO_4 > pure 2 N H_2SO_4 > H_2SO_4 at pH 3.0 > water alone. Of course the spent H_2SO_4 from Cyprus-Bagdad Mine contained soluble Cd, Cu, and Fe each in excess of 1000 $\mu\text{g/g}$. The order is valid, however,

even when not considering these elements. On the other hand, the order is reversed with respect to soil permeability. The more dilute the acid, the greater is the solution flow rate through soil. Nitric acid is also a good example of acid concentration effect on soil permeability and extent of element solubilization.

A comparison of H^+ concentration effects may also be made for organic acids such as water at pH 7.0, MSW leachate at pH 5.0, and acetic acid at 2 *N*. Constituent concentration in the effluent from the column of the same soil was as follows: acetic acid > MSW leachate > deionized water. The flux was roughly the reverse of this. Young MSW leachate contains volatile acids as well as higher molecular weight acids. Acetic acid often dominates in 1.5 year old leachates.

3. *Potential Pollutants in Spent Acid*

The capacity of the soil to attenuate or retain the potential pollutants contained in strong spent acids was very poor. By comparing data for Cu, Pb, and Zn movement through the same soil type as a result of receiving pure 2 *N* HNO_3 (Table 12) with that of spent 2 *N* Sylvania® HNO_3 (Table 17), it is apparent that the elements present in the spent acid are not appreciably attenuated. Lead, for example, was abundant in effluent from Davidson clay, Ava silty clay loam, and Nicholson clay in the Sylvania™ waste effluents, but was below detectable limits in the effluents receiving pure HNO_3 . The same lack of attenuation by soil occurs with the sulfuric acid pollutants Cd, Cu, Fe, and Al of Cyprus-Bagdad Co. (compare Table 13 with Table 19). Indeed, all metal pollutants in the strong acids, including the Wolverine® and spent phosphoric acid mix, are poorly held by soils.

The overwhelming H^+ ion mass action renders the soil almost wholly incapable of adsorbing and retaining soluble ions of metallic salts. Therefore, a specific metal prominent in spent acids may be expected to show up in equal prominence moving through a soil profile, assuming there is no lime present and the soil is permeable. However, consideration must be given to differences in the nature and concentration of the specific pollutant carried in the spent acid waste stream. At equal concentrations, one cannot expect Ni or Zn, for example, even at high H^+ ion concentration of the spent acids, to move through soil at the same rate as another element such as Al. Thus, despite the high hydrogen ion concentration, different metals still retain some individual characteristics with respect to rate of movement.

4. *Reduction/Oxidation Reactions*

The solubilization and movement of nearly all soil metals is greatly enhanced by the action of $[H^+]$ of H_2SO_4 at pH 3.0 and 0.25 *M* $AlCl_3$ + 0.025 *M* $FeCl_2$ solution at pH 3.0. At identical pH levels of 3.0, however, the reducing solution of $AlCl_3$ + $FeCl_2$ caused metal ions to migrate more rapidly (often by severalfold) from the soil columns than the H_2SO_4 . Thus, these reducing solutions, at least, can be considered more serious contributors to pollutant migration than their pH level may indicate and must be given special control attention in waste management on land.

5. *Kind of Acid Vehicle*

Nitric, sulfuric, phosphoric, and acetic acids do not solubilize constituents or move through soils at identical rates despite their applications at approximate equivalent H^+ ion activities. The 2 *N* nitric acid (Table 12) solubilized and mobilized the largest amount of metals from the four soils studied and 6*N* phosphoric acid the least. The differences for most metals are significant. Acetic acid was the most mobile and maintained soil permeability much longer (15 to 20 vs. 2 to 3 pvd) than the other acids. The organic acid flux remained fairly steady, unlike the inorganic acids, the flux of which declined after a few pvd to almost unmeasurable levels. Also, there was a lower concentration of metals (except for some metals in the phosphoric acid) contained in the acetic acid effluents than in the other acids.

Consistent trends for the spent acid-soil reaction are not as clear cut as for those for pure acids. In a comparison of flow rates, the spent 2 *N* Sylvania™ nitric acid infiltrated more readily than spent 2 *N* Cyprus-Bagdad™ sulfuric acid. On the other hand, Ava si c l is an occasional exception since its permeability to spent H_2SO_4 sometimes was equivalent to that of spent HNO_3 . The spent 8.8 *N* and 6 *N* phosphoric acid mixes were the least mobile of all acids and failed to move through the 20 cm of Davidson c, Ava si c l, and Nicholson c l in any appreciable amount. The same three soils were not fully wetted by 8.8 *N* H_3PO_4 , and with 6 *N* H_3PO_4 , Davidson c, Ava si c l, and Nicholson si c yielded 109, 19, and 14 mL, respectively, before flow completely stopped.

The apparent inability of spent 2 *N* Wolverine™ nitric acid to conform with the tendency towards faster movement of the nitric acids through soil is difficult to explain. Its penetration was even slower than the H_2SO_4 of Cyprus-Bagdad™ waste. Wolverine™ acid has a high soluble-salt content and a high Pb, Cu, Ti, Zn, and Zr content (Table 2); both factors appeared to have contributed to the clogging of pores and channels of transport to a greater extent than did the lower level of salts found in Sylvania™ nitric acid.

C. The Polluting Constituent

1. Cations

The disposal of strong spent acids subjects the environment to two sources of potential pollutants, namely, those originally in the spent acids and those solubilized from the soils. Those metals that are originally present in the spent acid wastes moved through the columns of soil almost uninhibited when associated with nitric and sulfuric acid wastes. For example, Cu, Pb, and Zn are present in spent 2 *N* Sylvania™ nitric acid in concentrations of 2400, 15,800, and 2850 $\mu\text{g/g}$ (Table 2), respectively. They appear in far larger quantities in soil-column effluents from the spent-acid treatment (Table 17) than in soils receiving pure nitric acid (Table 12). The same occurs with Cd, Cu, and Fe, in a comparison between Cyprus-Bagdad™ sulfuric acid (Table 19) and pure sulfuric acid (Table 13). The soil fails to attenuate the polluting metals contained in the vehicle of transport (i.e., the strong spent acids) in the presence of the high H^+ ion (cation) mass, low pH, and high soluble salt levels.

2. Anions

The vehicle of transport itself (spent acid liquids) may also contribute polluting constituents to the environment and groundwater. The most obvious pollutants are nitrates and phosphates. The nitrates of the spent nitric acid waste pose serious pollution problems because of their uncontrolled and rapid movement through soil when flow occurs. High nitrate concentrations are at the front of the flow as is illustrated by data reported in Figure 10. Such movement is sufficient evidence alone to prohibit placing of the spent acids on land in the necessary large concentrations for practical disposal.

The phosphates (PO_4 ions) of the spent 6 *N* and 8.8 *N* H_3PO_4 mix also move through soil. Sands are particularly susceptible to P migration. See data on Riverbottom sand (Table 20). Generally the soil is capable of retaining soluble mineral PO_4 ions, but where concentrations are high, such as in these spent phosphoric acids, the capacity of the soil to retain them can be exceeded. Thus, P can be undesirable pollutant to shallow water tables and underground aquifers, particularly if the soil is shallow, high in sands and gravel, or unusually coarse structured.

D. Soil Failure/Stabilization

The massive effect of H^+ ions of strong acids, 1 to 6 *N*, has been shown to cause the failure of soil, up to 20 cm deep, to retain associated heavy metals as well as elements commonly considered to be plant nutrients. Soil failure occurred readily through strong acid action in Riverbottom sand up to greater depths, 35.5 cm. (These soil depths have no

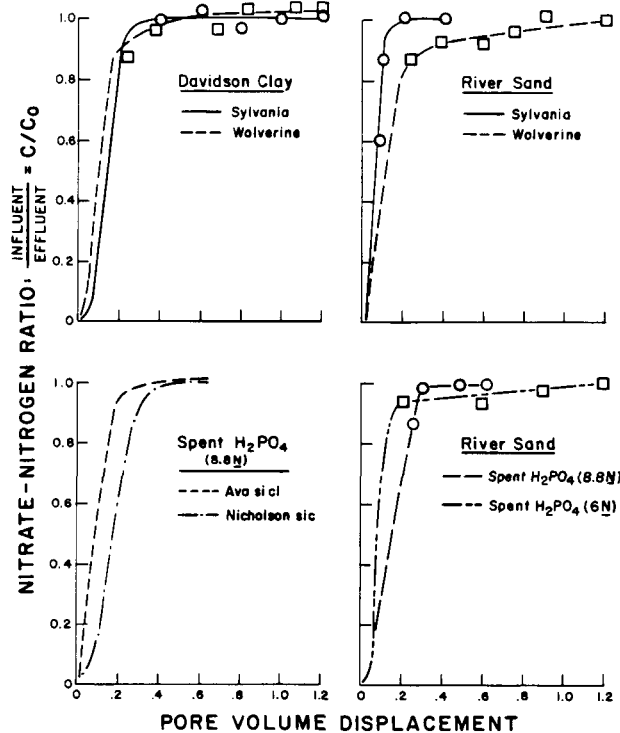


FIGURE 10. The rate of movement of nitrate-N from spent nitric and phosphoric acid wastes through soil and river sand. (From Fuller, W. H., Artiola, J. F., and Sheets, P., Effect of Hydrogen Ion Concentration of Acid Wastes on Soil Used for Disposal, U.S. EPA CORD Grant No. R807915-01 Rep., U.S. Environmental Protection Agency, Washington, D.C., 1982, 90.)

particular significance. They were selected after numerous trials to insure a maximum depth that would permit complete soil wetting with sufficient effluent delivery for analytical evaluation of the different soil-acid reactions.) The different acids, even at similar H^+ ion concentration and H^+ ion activity, did not flow through the soils at the same rate. Neither were different soils equally permeable to the acids. Permeability of soil to the most concentrated acids under study followed the order: 2 N acetic acid > 2 N nitric acid > 2 N sulfuric acid > 6 N phosphoric acid. Breakthrough ($c/c_0 = 1$) for the spent industrial acids (at similar acidity) for heavy metals carried in solution, usually occurred within one pore volume displacement for the 20-cm soil columns. Breakthrough for the same acid, H_2SO_4 , at pH 3.0 and for 0.025 M $AlCl_3$ plus 0.025 M $FeCl_2$ also at pH 3.0 varied for Fe and Al up to 20 or more pore volume displacements.

Packing the soil in the columns to bulk densities greater than their individual field conditions inhibited the rate of flow of strong acids through dry soil. Penetration of the soil by the 2 N and 6 N acids under conditions of dense packing (except river sand) was halted in depths as shallow as 6 to 8 cm for finer-textured Nicholson si c, Davidson clay, and Ava silty clay loam. Phosphoric acid and spent industrial phosphoric-acid wastes at 6 N and 8.8 N did not penetrate the 20-cm column of Nicholson si c even at loose packing, demonstrating that soils can stabilize the flow of concentrated acids to zero and prohibit further migration. The requirements for stabilization or establishment of a flow barrier to underground water are dependent on a dry soil, a favorable clay content, and a favorable packing or bulk density.

The possibility exists for using deep clay beds, depositing the acid waste, closing by

covering, and mounding of soil to prevent penetration of water. Dilute acids such as the pH 3.0 H_2SO_4 , highly reducing solutions such as $\text{AlCl}_3 + \text{FeCl}_2$ at pH 3.0, and acid landfill leachates at pH 5.0 flow through soil to great depths and, therefore, must be regarded as leaking sources, dependent almost wholly on the attenuation of associated pollutants. Stabilization via clogged pores, cementation of reaction products, and sealing of pore spaces by encrusting salts are not reliable mechanisms for practical disposal of dilute aqueous acid solutions and wastes streams, according to our present state of knowledge.

Two important characteristics of this research require some additional practical interpretation. The first is the condition of the soil with respect to its moisture as it may influence the behavior of strong acid wastes. In the experiments where the weaker acids, i.e., H_2SO_4 at pH 3.0, 0.025 M $\text{AlCl}_3\cdot\text{FeCl}_2$ at pH 3.0, and MSW leachate at pH 5.0, were involved, the soils were first saturated with water before introducing the acid influents. When the stronger pure acids, 2 N plus and industrial "strong" acid waste streams were studied, they were applied to air-dry soil. Had the soils been equilibrated at H_2O saturated conditions prior to application of the "strong" acids, results may have been different. Movement of soluble soil constituents and acid waste stream constituents may have been more extensive and the clogging and blockage of movement less suppressed. From the view of practical application, soil failure would appear to be sufficiently related to the absolute water content of the soil as to be one of the dominant factors in determining disposal management practice. Caution must be observed when applying the data presented here to soils other than air dry until similar experiments have been conducted on wet soils.

The second characteristic of these data that needs further practical interpretation is the mechanisms of soil clogging. Had the soil depths been greater than those used, there is no doubt that acid movement in all of the soils would have stopped. The accumulation of breakdown products of the soil combined with an increasing salt concentration and physicochemical precipitation would prohibit unlimited wetting of the soil as demonstrated in Figure 10. Thus, concentrated mineral acid movement through soils is self limiting, under dry soil conditions of arid lands, and in present circumstances, appears even less hazardous for disposal than is generally believed. Thus, in some cases it appears that high acid concentration may be a lesser hazard for land disposal than dilute acid concentrations.

REFERENCES

1. Behmer, D. E., Management of chemical wastes, in *Land Application of Waste Materials*, U.S. Department of Agriculture, Soil Conservation Society of America, 1976.
2. Behn, U. C., *Discharges of Industrial Waste to Municipal Sewer System*, Tech. Rep. No. 60, Cornell University Water Research and Marine Science Center, 1976.
3. Carlson, C. W., Land application of waste materials, in *Land Application of Waste Materials*, U.S. Department of Agriculture, Soil Conservation Society of America, 1976.
4. Hurst, R. E., Chemicals find growing use in oil fields, *Chem. Eng. News*, 48, 10, 1970.
5. Landreth, R., Research on impoundment materials, in 1st Annu. Conf. Advances in Pollution Control for the Metal Finishing Industry, U.S. EPA-600/8-78-010, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1978, 143 (PB 282-443/1BE).
6. Matrecon, Inc., Lining of Waste Impoundments and Disposal Facilities, EPA SW-870, OWWM, U.S. Environmental Protection Agency, Washington, D.C., 1980, chaps. 5 and 9.
7. Novak, I. and Cicel, B., Dissolution of smectites in hydrochloric acid. II. Dissolution rate as a function of chystallochemical composition, *Clay Clay Miner.* 26, 341,.
8. Watson, M. R., *Pollution Control in Metal Finishing*, Noyes Data Corporation, Park Ridge, N.J., 1973, 1.
9. Brown, K. W. and Associates, Inc., Hazardous Waste Land Treatment, EPA SW-874, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1980, chaps. 6 and 8.

10. **Grim, R. E.**, *Clay Mineralogy*, McGraw-Hill, New York, 1968, 434.
11. **Sinex, H. E.**, Dissolution of a Porous Matrix by Slowly Reacting Flowing Acids, M.S. thesis, University of Texas, Austin, 1970, 45.
12. **Anon.** Chemical resistance of asphalt coatings, *Mater. Prot.* 5, 81, 1966.
13. **Jenny, H.**, *The Soil Resource, Origin and Behavior*, Springer-Verlag, New York, 1980, 377.
14. **Artiola-Fortuny, J. and Fuller, W. H.**, Effect of crushed limestone barriers on chromium attenuation in soil, *J. Environ. Qual.*, 8, 503, 1979.
15. **Fuller, W. H.**, Liners of Natural Porous Materials to Minimize Pollutant Migration, U.S. EPA-600/S2-81-122, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1981, 1.
16. **Pearson, F. H. and McDonnell, A. J.**, Use of crushed limestone to neutralize acid waste, *J. Environ. Engin. Div., Amer. Soc. Civ. Engin. (EEI Proc.)*, Paper No. 1131, 139, 1975a.
17. **Pearson, F. H. and McDonnell, A. J.**, Limestone barrier to neutralize acid streams, *J. Environ. Engin. Div., Amer. Soc. Civ. Engin. (EEI Proc.)*, Paper No. 11382, 425, 1975b.
18. **Hoak, R. D., Lewis, C. J., and Hodges, W. W.**, Treatment of spent pickling liquors with limestone and lime, *Ind. Eng. Chem.*, 37, 553, 1945.
19. **Gehm, H. W.**, Neutralization of acid waste with an up-flow expanded limestone bed, *Sewage Works J.*, 16, 104, 1944.
20. **De Vitte, T. W., Isaac, G. A., and Laseke, B. A.**, Status of flue gas desulfurization systems in the United States, *Flue Gas Desulfurization*, U.S. Environmental Protection Agency Symp., U.S. Environmental Protection Agency, Washington D.C., 1976, 84.
21. **Artiola-Fortuny, J. and Fuller, W. H.**, Limestone liner for landfill leachates containing beryllium, cadmium, iron, nickel, and zinc, *Soil Sci.*, 129, 167, 1980.
22. **Fuller, W. H.**, Investigation of landfill Leachate Pollutant Attenuation by Soil, U.S. EPA-600/2-78-158, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1978, 219.
23. **Korte, N. E., Skopp, J. M., Niebla, E. E., and Fuller, W. H.**, A baseline study of trace metal elution from diverse soil types, *Water Air Soil Pollut.*, 5, 149, 1976.
24. **Richards, R., Ed.**, Diagnosis and Improvement of Saline and Alkali Soils, Agric Handbo. No. 60, U.S. Department of Agriculture, Washington D.C., 1954, 160.
25. **Marion, G. M., Hendricks, D. M., Dutt, G. R., and Fuller, W. H.**, Aluminum and silica solubility in soils, *Soil Sci.*, 121, 76, 1976.
26. **Murmann, R. P. and Koutz, F. R.**, Role of soil chemical process in reclamation of wastewater applied to land, in *Wastewater Management of Disposal on Land*, Special Rep. No. 171, U.S. Army Cold Region Research and Engineering Laboratory, Hanover, N.H., 1972, 183.
27. **Fuller, W. H., Amoozegar-Fard, A., and Carter, G. E.**, Predicting movement of selected metals in soils: application to disposal problems, in *Municipal Solid Waste: Land Disposal*, Shultz, D., Ed., 5th Annu. Res. Symp., EPA-600/9-79-023a, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1979, 358.
28. **Fuller, W. H. and Alesii, B. A.**, Behavior of municipal waste leachate. II. In soil, *Environ. Sci. Health*, A-14, 559, 1979.
29. **Fuller, W. H., Amoozegar-Fard, A., Niebla, E., and Boyle, M.**, Behavior of Cd, Ni, and Zn in single and mixed combinations in landfill leachate, in *Land Disposal: Hazardous Waste*, Shultz, D., Ed., Proc. 7th Annu. Res. Symp., U.S. EPA-600/9-81-0026, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1981, 18.
30. **Amoozegar-Fard, A., Fuller, W. H., and Warrick, A. W.**, Predicting movement of selected polluting metals in soils, *J. Environ. Qual.*, in press.
31. **O'Donnell, D. F., Alesii, B. A., Artiola-Fortuny, J., and Fuller, W. H.**, Predicting cadmium movement through soils as influenced by leachate characteristics, in *Management of Gas and Leachate by Leachate Characteristics*, in *Management of Gas and Leachate in Landfills*, Banerji, S. K., Ed., Proc. 3rd Annu. Municipal Solid Waste Res. Symp., U.S. EPA-600/9-77-026, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1977, 159.

Site Selection, Monitoring, and Closure



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

Chapter 7

SITE SELECTION, MONITORING, AND CLOSURE

I. RATIONALE AND SCOPE

An analysis of past experiences for selecting the methods and locations of industrial and municipal waste disposal indicates that too much emphasis has centered on:

1. Land costs
2. Nearness to waste sources
3. Ease of acquiring the land
4. Ease of site approval

Chance selections have produced the biggest headaches and have caused considerable environmental problems. In the worst examples, damage to water and soil quality that are extremely costly to clean up occur (e.g., the need for large "super" funding).

As we learn more about the long-term consequences of disposal of wastes, considerably more effort will be directed toward securing sites and methods which can best provide protection of groundwater and the food chain. Site selection methodologies are just now emerging from the large amount of information available on the environment. Ryan and Loehr,¹ for example, state that the basic problem confronting the design engineers is the way to locate the (1) most cost-effective and (2) technically feasible site within a reasonable distance of a given waste source. Ideally, decisions are based on new technology, comprehensive site evaluation prior to site construction, public review and approval, land use consideration, long-term care of the site, safety, and alternative methods of "safe" managing waste disposal. Therefore, the purpose of this chapter is a discussion aimed at the integration of site selection, premonitoring, monitoring, closure, and postmonitoring of the waste site.

Monitoring the environment is an essential function in the selection, operation, and closure of any waste disposal site. It should provide the necessary warning signals of pollutant behavior in the disposal environment, well in advance of possible contamination of the food chain and groundwater. Monitoring should establish confidence in the design and management of the waste disposal facility. Management depends on the monitoring program to develop guidelines for acceptable methods of application and rates of land loading of wastes.

Closure should not carry a connotation of termination of all functions at the disposal facility as the last load of waste is accepted for treatment. Although waste disposal is discontinued and daily covering satisfied, monitoring and site maintenance must continue. Protection of groundwater and food chains is a continuing program. Land-treated wastes may require occasional soil cultivation, pH adjustment, and, in arid lands, sprinkling or irrigation to maintain biodegradation. Some types of disposal will need revegetation, plant cover maintenance, continued erosion control practices, and runoff control maintenance. Gas production and subsidence also require special attention.

II. SITE SELECTION

A fund of information is required to begin the search for a suitable site for waste disposal. The principal objective in the site selection for all waste disposals is to choose appropriate locations for the purpose of degrading, stabilizing, retaining, or otherwise rendering innocuous those wastes receiving such treatments. Obviously, the kind of waste to be disposed of and its composition must be known before the search begins. Identification of the broad treatment media should involve:

- The land
- The atmosphere
- The vegetation

The general criteria for selection, therefore, must define the site with respect to these components of the treatment media as the various wastes are expected to interact with them in the disposal system. No two systems will be alike. No two systems are expected to utilize the three treatment media — land, atmosphere, and vegetation — to the same extent. Vegetation requirements may be minimal for certain burials, for example, but highly important in land treatment for recreation or agricultural production. Similarly, the atmosphere may be involved minimally for some solid waste disposals, but maximally in exposed surface disposals of organic solvents.

A. General Criteria

Certain methodologies must be developed for the selection of appropriate sites for any waste treatment as addressed in Chapters 2, 3, and 4. Those characteristics of the site which can be managed and operated for acceptable performance as a system must be identified to utilize the natural biological, chemical, and physical processes in the treatment media for absorption, degrading, retaining, or otherwise abating those wastes receiving treatment. Therefore, the general criteria for decision making in the selection of acceptable sites are minimization of migration or transportation of polluting constituents from the place of waste deposit and maximizing the facets of biodegradation, pollutant retention, and stabilization. In short, decision criteria for selection must center around:

1. Minimization of off-site contamination of the total environment
2. Flexibility to accommodate risk of accidental explosion, spills, and sudden release of polluting and/or toxic substances into the atmosphere
3. Irrevocable disposal, since once the site is selected and the operation begins, the latitude of design and management are defined by the site characteristics
4. The specific nature of the waste intended for disposal and expected variability in composition. The flexibility in the choices for containment prior to disposal resides mainly in the site itself rather than the waste
5. A facility which must provide the public with assurance that the quality of human and animal health will not be sacrificed nor the quality of the surrounding environment diminished

The most desirable criteria to keep in mind during the screening process of site selection are

1. The complete and neat elimination of the wastes
2. The elimination of the hazards of point-source concentration of pollutants
3. The elimination of noxious odors and aerosol problems
4. The safe and sanitary disposal of human, animal, and plant pathogens
5. The conservation of natural resources (organic matter, plant nutrients, water)
6. The enhancement of biodegradation and disease control
7. The conservation of energy by waste utilization
8. The distribution of wastes on upland rather than bottomland and river channels subject to flooding
9. The soil which has a favorably fine texture and depth to minimize translocation and off-site contamination of groundwater, food chains, surface water, and the atmosphere

B. Types of Land Disposal

A screening protocol is desirable for all site selections involving land disposals. The final selection will depend on many factors, one of which is the type of land disposal facility best suited for the specific waste. For example, there are

1. Burials
2. Encapsulations
3. Well injections
4. Infiltration/irrigation
5. Impoundments
6. Land treatment/resource utilization systems as major systems

Each has its own unique site requirements. Although the most desirable site for the particular type of disposal is sought, seldom is the ideal site found. Usually, only best choices, on a comparative basis, are available for selection, and compromises must be evaluated against each other. The final choices determine the design constraints and constraints dictated by operations and management.

Despite the great variability in choices of types of land disposals, there are certain basic site requirements that all share. Highly specific design constraints for each type must necessarily be imposed in addition.

Those types of land disposals that depend wholly on the natural parameters of the site environment to contain the waste without aid from plastic liners, encapsulation, and water-controlling devices (ditching and/or pumps) require more ideal site properties and designs (e.g., deeper soil layers, finer textures, greater distance from aquifers) than those utilizing plastic liners and/or containers. The purpose of this chapter is not to offer specific site designs for the various types of land disposals, but rather to emphasize the characteristics most important to securing sites which can best provide protection of groundwater and the food chain.

During the site selection procedure, the kind of waste to be land treated and type of land disposal most suited must be identified to obtain the most acceptable site because the requirements differ for the various types of disposal. For example, burials of municipal solid waste in sanitary landfills require greater depths of soil than surface treatment of municipal sewage sludge. The excavation of the land for the landfill can greatly reduce the effective thickness of the soil layer, so necessary as a pollutant treatment medium. Moreover, biodegradation of the same waste in a landfill is slower and less complete than when surface incorporated, such as in land treatment. Runoff and erosion control, also, require different soil characteristics of topography and hydrology for the different types of disposal methods. Management and operation activities as supplements to acceptable disposal, also, will differ in some particular aspects. Similarly, site requirements for solution impoundments emphasize the need for special soil properties to prevent vertical solution migrations, whereas infiltration systems require some leakage, and thus it is the same with specific requirements of all the different types of disposal methods.

C. General Steps to Site Selection

Only by preparing rigid guidelines for site selection can the objectives of safe and secure disposal be assured. Although, as pointed out, specific requirements for each type of waste disposal vary, the broad requirements of an acceptable site are quite similar. To avoid unnecessary repetition, the remainder of the discussion on site selection is oriented on the intricacies of the most desirable characteristics for land treatment (LT) as an example. The compilation of information, organization of factors influencing retention of potentially hazardous wastes (solids, slurries, and waters), and identification of the procedures to follow

for pollutant stabilization will provide a basis for understanding the concept of design for a land treatment facility. Site selection as planned here must first and foremost observe all restraints to assure that pollutants do not enter the food chain environment and to assure that the quality of underground water sources forever remain free from chance pollution.

1. Approach

Currently, there is no clearly defined protocol for evaluating the efficiency and safety of land treatment for managing a given waste. A condition for establishing a land treatment facility is the determination and development of evidence that a certain waste can be beneficially treated in a given habitat (e.g., soil, topography, climate, etc.). Further, a condition for the establishment of a facility should be based firmly on an informed selection process for a site rather than on chance, haphazardly. Specific characteristics of the waste and site are interdependent and must be considered together in determining acceptable land areas.

Following is a proposed step-by-step approach for site selection. They are not considered as the “final word”, but are to identify key aspects to be considered.

Step 1: Reconnaissance for acceptable land areas and initial screening. A preliminary screening survey should be made of lands within the most desirable geographical and transport areas to be used for land treatment Table 1. Maps, surveys, and reports that identify certain site features should be obtained to determine:

1. Soil types and the real extent of each
2. Geologic formations — karst, aquifer, sinkholes
3. Highways, roads, and railroads
4. Topography, landscape (e.g., excessive slopes, Lithosols, rough and broken rock outcrops)
5. Land uses (e.g., airports, industrial, and institutional)
6. Vegetative cover
7. Disturbed land
8. Water bodies — lakes, rivers, streams, wells, and springs
9. Unsited landforms
10. Population distribution

This initial screening is designed to identify and locate, early in the site selection process, land features in the target area for the purpose of saving time and effort by early elimination of areas that do not meet the minimum standards for land treatment/utilization (Table 1). It is presumed that the areas eliminated, at this point, clearly do not meet the quality of characteristics necessary either to ensure adequate protection of ground or surface waters or to provide adequate waste treatment and stabilization. A suitable rating attained from an evaluation based on the above criteria moves the site selection along to Step 2 (Table 2).

Step 2: Rating of the soil characteristics. Step 2 is designed to rate soil properties (Table 3) which predominantly affect the performance of biodegradation, attenuation, and immobilization at any given site. The table is untried, but, nevertheless, addresses the key factors.

Prominent soil physical related properties

1. Particle size separates using the USDA classification
2. Total particle surface area (Figure 1)
3. Bulk density (compaction)
4. Soil texture stratification
5. Subsoil restrictive layers (Figure 2)
6. Hydraulic conductivity

Table 1
UNACCEPTABLE LOCATION FEATURES WHICH WILL RESULT IN THE
ELIMINATION OF A SITE FROM FURTHER CONSIDERATION FOR LAND
TREATMENT: STEP 1

The proposed site is not situated such that the treatment area of the facility will be located — unless drastically altered to ensure complete containment of hazardous constituents by construction management. **Severe limitations E^a**

- | | |
|--|--|
| <p>A. On unsuitable landforms of</p> <p>Floodplains: 100 year (U.S. EPA Fed. Reg. Sec. 264.18(16), p. 32290)</p> <p>Moraine: Highly heterogeneous materials of geologic debris including sands, gravels, stones, boulders, and rock fragments all mixed together</p> <p>Drumlins: Limited areas on steep slopes</p> <p>Filled Valleys: Highly heterogeneous materials</p> <p>Coastal Planes: Highly heterogeneously mixed geologic debris that is usually very porous</p> <p>Deltas: Frequently flooding</p> <p>Tidal Flats: Frequent flooding, salty</p> <p>Sand Dunes: Wind erosion, shifting sands, highly porous, poor attenuation</p> | <p>_____</p> <p>_____</p> <p>_____</p> <p>_____</p> <p>_____</p> <p>_____</p> <p>_____</p> |
| <p>B. Over unsuitable geological and hydrogeological formation</p> <p>Karst: Porous, fractured, stratified limestone.</p> <p>Volcanic Cinders and cinder materials : Porous, coarse texture</p> <p>Rock Outcrops:</p> | <p>_____</p> <p>_____</p> <p>_____</p> |
| <p>C. On unsuitable hydrological areas of</p> <p>Seasonally high water table: Within 2 meters of the surface; may be acceptable with adequate drainage</p> <p>Wetlands: Permanently swampy and wet, bogs</p> <p>Within 150 meters of a well that is or will be a source of water supply for any use</p> | <p>_____</p> <p>_____</p> <p>_____</p> |
| <p>D. On unsuitable soils with</p> <p>pH values less than 5.5</p> <p>Shallow depth of soil, < 2 ft</p> <p>Slopes greater than 6%</p> <p>Highly restrictive subsoils completely impermeable within 2 ft depth</p> <p>Excessively permeable sands gravels, rocks and stones</p> <p>Classifications of saline, saline/alkaline, and alkaline land</p> <p>Severe soil ad/or wind erosion</p> | <p>_____</p> <p>_____</p> <p>_____</p> <p>_____</p> <p>_____</p> <p>_____</p> <p>_____</p> |
| <p>E. On undesirable land use areas of</p> <p>Polluted and/or contaminated land</p> <p>Upwind of population centers</p> <p>Rough and broken land, stone and cobbles predominate</p> <p>Wilderness areas inaccessible to operations</p> | <p>_____</p> <p>_____</p> <p>_____</p> <p>_____</p> |

^a Insert E (elimination) in checklist at the right, if applicable.

Site: _____

Table 2
DESCRIPTIONS AND DEFINITIONS OF SUITABILITY RATINGS

Suitability class	Class no.	Description and definition
Highly Suitable	4	No limitations nor major design constraints identified for HWLT and the evaluating characteristics are within the most desirable concept of an HWLT facility
Moderately Suitable	3	Some limitations that may be overcome or corrected with minimum effort and cost, to bring the site to the desirable quality for an HWLT facility
Suitable	2	Some limitations that may be overcome or corrected with reasonable effort and cost, but still worth the cost because of other very desirable features
Poorly Suitable	1	Limitations that may be overcome or corrected with very great effort and cost to bring the site to a desirable condition for an HWLT facility
Unsuitable	E	Unalterable characteristics that limit establishment of an HWLT facility and is eliminated

7. Available water-holding capacity (WHC)
8. Permeability and infiltration rates
9. Soil depth
10. Soil drainage classes
11. Soil and water loss

Prominent soil chemical related properties

1. Soil pH
2. Cation-exchange-capacity (CEC)
3. Hydrous oxides of Fe (Mn, Al)
4. Total dissolved solids (TDS) — EC_c
5. Dominant clay minerals

Step 3: Rating of the landscape and topography (Table 4)

1. Topography—slope, frequency of slopes
2. Soil erosion—gully, rough and broken land
3. Land use—residential, outdoor recreation, industrial, crop land, orchard, forest, range, idle, swamp, and disturbed land
4. Landforms

Step 4: Rating of the hydrology and geohydrology (Table 5)

1. Depth to bedrock, hardpan, or other impervious layers
2. Groundwater quality
3. Depth to groundwater and capillary fringes
4. Presence or absence of aquifer (aquicludes and aquitards)
5. Thickness of unconsolidated sediments and residual soils
6. Karst topography (clayey residual soils overlie limestone or dolomites)
7. Water sources—well, lake, stream, rivers, ponds, and marshes
8. Flooding frequency and wet lands

Table 3
STEP 2 RATING SCALE OF SOIL CHARACTERISTICS FOR HWLT SITE SELECTION

Soil parameters	Rating (points)					Score*
	4	3	2	1	E	
Salt and alkali (%)	0—0.15	0.15—0.35	0.35—0.50	0.50—0.65 reclaimable	> 0.65 nonreclaimable	
Hydraulic conductivity cm/sec (in top 60 cm of soil)	10^{-3} to 10^{-2}	10^{-3} to 5×10^{-4} or 10^{-2} to 5×10^{-2}	5×10^{-4} to 10^{-4} or 5×10^{-2} to 10^{-1}	10^{-4} to 5×10^{-5} or 20^{-1} to 5×10^{-1}	$< .5 \times 10^{-5}$ or $> 5 \times 20^{-1}$	
Available water holding capacity (in H ₂ O/ft of soil depth)	>1.5	<1.5 to 1.0	<1.0 to 0.75	< 0.75 to 0.5	< 0.5	
Wetness class	Well drained	Moderately well drained	Somewhat poorly drained, somewhat excessively drained	Poorly drained	Very poorly drained, or excessively drained	
Particle size distribution (top 60 cm of soil)	Loam, silt loam, sandy clay loam	Sandy loam, silty clay loam, clay loam	Sandy clay, silty clay	Loamy sand, silt	Sand, clay, muck	
pH	≥ 7.0	< 7.0 to 6.5	< 6.5 to 6.0	< 6.0 to 5.2	< 5.2	
Cation exchange capacity (mg/100 g)	> 25	<25 to 15	< 15 to 10	< 10 to 5	< 5	
Soil depth (m)	> 5	< 5 to 3	< 3 to 2	< 2 to 1	< 1	
Restrictive subsoil layer	None	Slightly restrictive	Moderately restrictive	Highly restrictive	Severely restrictive	
Sum						

* The scores for each feature are recorded in the last column and summed on the last line. Any value of E eliminates the location as a possible site.

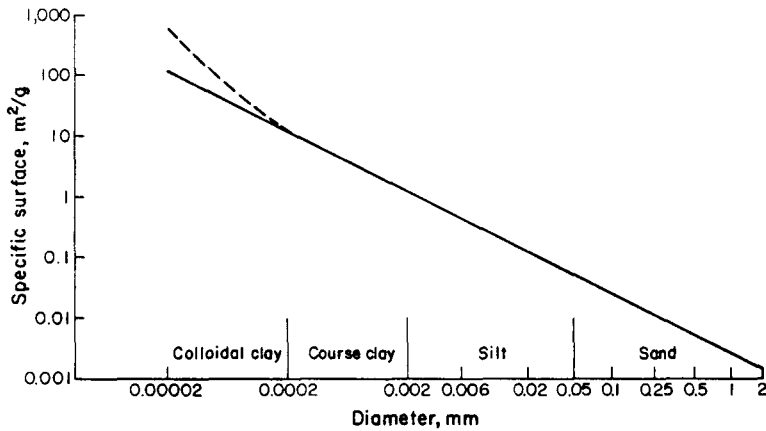


FIGURE 1. Relationship between particle size of soil fractions and their approximate specific surfaces. (The full line represents the relation between the size of spheres of density 2.65 g/cm^3 and their specific surfaces. The broken line takes into account that clay particles are more nearly plate shaped and that the fine clay has much internal surface.) (From Konke, *Soil Physics*, McGraw-Hill, New York, 1968, 87, 224. With permission.)

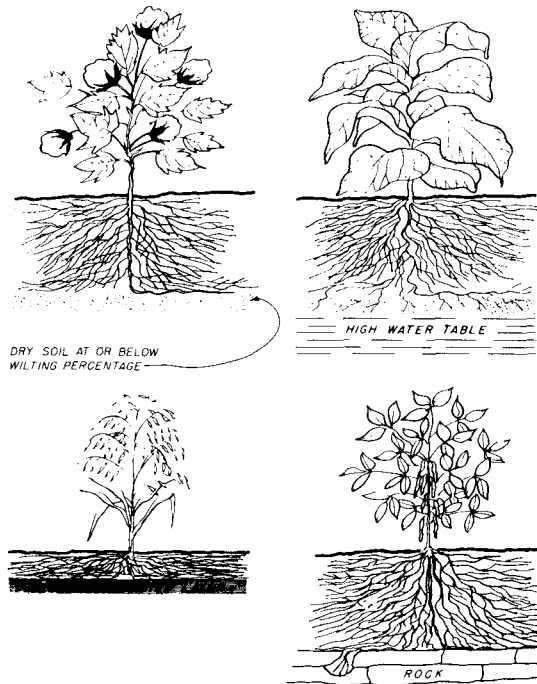


FIGURE 2. Some subsoil restrictive layers that can influence rate of downward water penetration as well as growth of vegetation are illustrated in the four common conditions of dry soil, high water table, compaction, and shallow rock, caliche or iron pans. (From U.S. Soil Conservation Service, *Engineering Handbook*, Section 15, *Irrigation*, Soil-Plant-Water-Relationship, U.S. Government Printing Office, Washington, D.C., 1964, chap. 1.)

Table 4
STEP 3 RATING OF LANDSCAPE AND TOPOGRAPHIC CHARACTERISTICS ON A BASIS OF NUMERICAL CLASSES

Landscape and topography	Rating (points)					Score ^a
	4	3	2	1	E	
Predominant slope range—%	1—2	0—3	2—4	4—6	> 6	
Soil erosion susceptibility class (USDA-SCS, 1983)	No erosion problems USDA-SCS Class I	Slight erosion; easily corrected USDA-SCS Class 2	Slight, but not easily corrected USDA-SCS Class 2	Serious erodability, can be corrected USDA-SCS Class 3	Serious erosion; not correctable USDA-SCS Class 3 & 4	
Land capability classification—% USDA-SCS (1973)	Cultivated Class I—100%	Cultivated with modification Class I—75% Class II—25%	Cultivated Class I—50% Class II—50%	Cultivated Class I—25% Class II—75% Noncultivated pasture Class II—75% Class III—25%	Cultivated Class IV through Noncultivated Class VIII	
Land site modification; filling; clearing of vegetation; dyking; barriers; construction	None	Small area, 10% low cost	Acceptable area of 10—20% moderate cost involved	Large area of 20—50% costly	Large area costly > 50%	
Average or Sum						

^a The scores for each feature are recorded in the last column and summed on the last line. Any value of E eliminates the location as a possible site.

SITE: _____

Table 5
STEP 4 RATING OF HYDROLOGICAL AND HYDROGEOGRAPHICAL
CHARACTERISTICS FOR HWLT SITE SELECTION

Hydrogeographical and hydrological parameters	Rating (points)					Score*
	4	3	2	1	E	
Depth to ground water (m) (regional)	≥ 50	50 to 20	20 to 3	3 to 2	< 1	_____
Depth to seasonal high water table (m)	≥ 6	6 to 4	4 to 3	3 to 2	< 1	_____
Depth to bedrock (m)	> 10	10 to 6	6 to 3	3 to 1	< 1	_____
Ground water quality EC = mmhos/cm	0.75	0.75 to 1.5	1.5 to 3.0	3.0 to 7.5	> 10	_____
Sum						
Site: _____						

* The scores for each feature are recorded in the last column and summed on the last line. Any value of E eliminates the location as a possible site.

Step 5: Final evaluation— The site reviewed is abandoned if it is eliminated for any of the characteristics in Step 1. Those sites that pass to Step 5 are then (Table 6) evaluated on a basis of total sum of points from Steps 2, 3, and 4. These numerical evaluations will then receive a final review based on climatic location and local public input. Perhaps each parameter should be evaluated independently rather than on a weighted-average basis so that the importance of each parameter to the overall evaluation can be assessed. Strictly weighted-average methods should be avoided for two reasons: (1) the weight assigned to a given parameter is made on a subjective basis and (2) the relationships among parameters are not necessarily additive. For example, assume that a site under consideration is evaluated on only three factors: land use, soils, and geologic conditions. After initial evaluation, excellent marks in the land use and soils are scored, but the site lies over an active fault. When weights and values are assigned to each parameter and the scores are summed, it is possible that this site could come out well ahead of other sites which have moderate marks for all parameters. Locating disposal facilities over active faults is entirely out of the question. This particular example may be extreme, but it points out the weakness of the weighted-average method of interpreting the results of site selection.

Another guideline for developing well-reasoned site criteria is that the criteria should establish certain minimum performance standards. By establishing minimum standards, the site which is ultimately selected will be not only the most favorable among those considered, but it will be acceptable from the standpoint of each major site parameter.

The use of a computer in paring the major search area down to a discrete number of minor search areas can have certain advantages:

1. It is objective.
2. It makes use of available information.
3. It minimizes subjective judgments.
4. It considers the entire major search area rather than arbitrarily selected locations within the major search area.
5. It is very fast. As long as the raw data is in place, the rate-limiting factor is the time necessary to formulate an acceptable rating system.
6. It is relatively inexpensive.

Table 6
STEP 5 RATING OF LAND CHARACTERISTICS FOR
FINAL SCREENING FOR THE SELECTION OF
SUITABLE HWLT SITES

Characteristic used in evaluating HWLT sites	Individual score	Step	
		Number	Scores
Reconnaissance for elimination of unsuitable sites	E	<u>1</u>	___
Prominent slope range			
Soil erosion			
Land capability class			
Land site modification		<u>2</u>	___
Soil salinity			
Hydraulic conductivity			
Available water holding capacity			
Drainage class			
Particle size distribution			
pH (Acidity)			
CEC (Cation exchange capacity)			
Soil depth			
Restrictive subsoil layer		<u>3</u>	___
Depth to ground water			
Depth to seasonal high water table			
Depth to bedrock			
Ground water quality		<u>4</u>	___
Sum			
HWLT site identification			
Relative rank:			
Evaluator(s):			
Date evaluated:			

Despite its strengths, the computer assisted site selection technique has obvious limitations:

1. The accuracy of the raw data are highly dependent on the age and completeness of the original source. It is also dependent upon the person interpreting the data.
2. There are limitations to the kind of data stored in the computer.
3. The collective judgments of a panel of "experts" may introduce individual biases into the interpretation of the results.
4. Even though certain conclusions can be reached following the computer assisted process, project organizers must understand that considerably more time and resources must be expended to reach conclusions regarding the final site selection.

III. MONITORING

A. General Criteria

Monitoring is a necessary function of all waste disposals.²⁻⁵ As used here, monitoring is to check, test, and observe for the special purpose of keeping track of, regulating, and controlling the operation of waste disposal facilities. This involves the performance of the disposal facility, testing the quality of the contacted natural systems and surrounding off-site environment, and observing and recording measurable changes in the quality of the facility environment. Moreover, it should be programmed to confirm the assumptions made

in the land disposal design and establishment of the land disposal facility. Consequently, it should not be substituted for utilizing our best knowledge and judgment of the many environmental relationships within any land disposal design prior to implementation of the facility.

More specific functions of a monitoring program identify and quantify the broad environment, i.e., soil, atmosphere, and vegetation, and the components of the specific soil-waste environment, i.e., the soil (sand, silt, and clay), the vehicle of transport (water and solvent), and pollutant itself (heavy metal, toxic organic components, and nontoxic organic constituent). The monitoring program, thus, requires that periodic sampling and analyses be made of:

1. The waste—loading and degradation of the waste
2. The soil—natural and waste contacted, solution at different depths
3. The vegetation—both in contact with waste and with off-site plants
4. The hydrology and geohydrology
5. The biodegradation of organic constituents
6. The microorganisms having health impact—e.g., *E. coli tirus*
7. The groundwater quality through well analyses
8. The erosion and runoff waters

Included are premonitoring, on-site monitoring, and postmonitoring of the facility and treatment as follows.

1. Premonitoring

Premonitoring is the first step in the selection of a site for waste disposal to establish baseline data and to furnish information for developing predictions and design judgments for the operation and management of the treatment facility.⁵ Premonitoring cannot change the facts, however, it can:

1. Identify the important components of the environment and in this way contribute to the selection of the most suitable site
2. Evaluate the containment control practices necessary for long-term pollution abatement
3. Determine the intensity of the remedial containment control practices to ensure long-term pollution stabilization
4. Form a base level of environmental quality as a reference for permissible deterioration during site usage
5. Characterize the waste and thereby aid in selection of the design for containment of the pollutant

Premonitoring for site selection includes all of those items covered under site selection just discussed. Some of the data will already be available and some will have to be measured on site. The most prominent factors are

1. Climate—amount and distribution of rainfall, temperature, freezing and thawing, and wind
2. Land topography—slope, contours, drainage patterns, and watersheds
3. Soils—chemical and physical properties and hydraulic characteristics
4. Surface and subsurface water, drainage, and flood patterns
5. Vegetation—kind and density
6. Position of underground aquifers and water tables, depth, quality, and flow patterns
7. Well locations and water quality

Premonitoring of waste characteristics includes the quantification of:

1. Organic matter content or total organic carbon (TOC)
2. Heavy metal content and concentration
3. Electrical conductivity of aqueous leachate and solution (EC) or total dissolved solids
4. pH (acidity or alkalinity) and normalities
5. Toxic organics
6. Solvent content and kind of solvent

2. *Monitoring During Disposal*

The general criteria for monitoring during disposal and facility activity are similar to those of premonitoring, but the emphasis is more on groundwater quality and food chain protection. Sampling must be frequent enough to identify any hazard well before its onset and follow the fate of the potential pollutants until they are biodegraded, stabilized, or otherwise rendered innocuous.

3. *Postmonitoring*

Monitoring continues after closure to insure the residual effects have been unquestionably controlled. Of particular concern is the protection of groundwater, food chains, and runoff of surface waters or, in short, the vehicles of transport including soil, water, and wind erosion. The establishment of vegetation and assurance of its maintenance are required for some period of time after closure.

B. Waste Properties

Monitoring programs are developed for waste evaluations at the sites to determine the uniformity in composition of waste being brought onto the facility to determine the rate and extent of biodegradation for loading rate adjustments and to ascertain the persistence of the original toxic constituent and/or residual accumulations of intermediate decomposition products. Accumulations of common salts of such cations as calcium, magnesium, sodium, and potassium and nutrients such as nitrates and phosphates have been known to develop from heavy or long-term applications of sewage, sewage water, canning residues, and other highly organic residues. Unusual accumulations of these types of salts not only inhibit further biodegradation of the waste, but growth of plant life that may be expected to be established or cropped. Wastes that contain elevated quantities of heavy metals must be monitored prior to application as well as in the surface layers of soils to ascertain the accumulated concentration as a warning to keep within the permissible threshold values. Each waste possesses different quantities and qualities of pollutants. Sampling and analyses procedures, therefore, will vary according to the specific waste being treated. Wastes whose composition varies erratically require more frequent sampling and more intensive monitoring than those wastes generated more continuously and which are more uniform in composition. For land treatment, both the annual application rate and allowable cumulative application rates must be adjusted to variabilities in composition. Extra attention in land treatment must be provided for those wastes close to the limiting values for safety, perhaps within 25% of the level at which they become limiting.

C. Landscape and Topography

Landscape is what the area looks like. It is not measurable. The operator of facilities for disposal that change the appearance of the landscape must contend with public comment. Monitoring of landscape which includes vegetation may involve no more than a vegetation accounting of the site prior to disposal and photographs of the predisposal area as a record for returning the closure back to its original or an even better state of landscape.

Topographic contour maps are relatively easy to obtain. Topography is an essential part of site location selection and design. Both surface and subsurface water, that represent the vehicle carrying the potential pollutant, move directionally as topography dictates.⁶ The ratio of water infiltration/runoff is determined by topography. Soil and water erosion hazard also relate to topography.

D. Soil Properties

Premonitoring should be undertaken to evaluate the soil properties that influence migration rates through soil and their interaction with other components of the disposal site environment. Sometimes only a few simple exploratory analyses will suffice.

1. Physical

Control of migration of toxic constituents generally begins with some modification of the soil. Natural soils develop distinct horizons that differ in texture, structure, compaction, thickness and inorganic and organic accumulations. Physical soil characteristics that influence migration rate of pollutants are listed earlier in the chapter.

Monitoring the soil prior to site selection may well include an ultradetailed soil survey. The quantification of those soil properties influencing pollutant migration rate may readily be undertaken on soil samples taken from field borings. Borings should be made to at least the depth of the soil C horizon and into the unconsolidated geologic material below, depending on the configuration of the expected excavation. Since soil removed from the excavation may be returned, in part at least as liner or as soil covering, analyses should be made for its characterization. An experienced soil scientist can identify soil textures within reasonable limits in the field during the boring procedure. This will save considerable time and will allow excavation to begin immediately as textural layers can be plotted for stockpiling for liner use.

The soil should be adequately characterized by monitoring and the unconsolidated material below identified. For example, if the land is fairly uniform in physical characteristics, perhaps 2 to 3 borings per hectare to a depth of 15 m or to drill-refusal should be adequate prior to excavation. Most landfill managers want to know the depth to bedrock. Both shallow (5 to 7 m) and deep (10 to 50 m) borings should be made with the less costly shallow borings dominating in number. Some soils will require a depth sample as frequent as every 30 cm at least for the shallow test holes; others may well be characterized only at meter intervals. Sample size varies from 0.5 to 1.0 kg, depending on the analyses required. Only the shallow depth soil samples are necessary for land treatment disposal option. However, depth to bedrock should be known for all waste disposal sites.

2. Chemical

Monitoring the soil samples taken from the prospective sites should include an analysis for the chemical soil characteristics identified earlier in the chapter. The depth of soil sampling and frequency of sampling will depend on the type or method of disposal and extent of the site.

E. Hydrology and Geohydrology

Monitoring the quality of the groundwater is prompted by environmental and legal sensitivity to potential water contamination. This is particularly emphasized where waste disposal facilities exist. Prior to implementation of groundwater monitoring, certain preliminary information is needed:

1. The waste characteristics and most toxic constituents
2. The conditions of the hydrologic framework
3. The geologic (and man-induced) features affecting the water movement
4. The groundwater use
5. The groundwater characteristics such as depth, aquifers flow patterns, fluctuations, and perched water tables
6. The groundwater quality
7. The seasonal fluctuations both in quantity and quality
8. Climatological setting

1. Well Monitoring

Monitor wells are a prominent feature of a successful monitoring program. Well installations are highly site specific and cannot be established without first visiting the site. References for determining which combinations best fit into a particular site and complement a particular monitoring program have been suggested.^{7,8} The more site specific monitoring information may be found after the waste characteristics and site location are known.⁷

Field installations require extensive planning to ensure optimum characterization of the groundwater and contamination monitoring. Important items for consideration are

1. Proper vertical and horizontal placement
2. Proper selection of sampling equipment best suited to satisfy the objectives
3. Placement in the flow pattern that is representative of the possible contamination from the disposal
4. Identify as many of the physical and hydrologic characteristics of aquifer as possible

A diagram of an actual monitoring well plan is provided in Figure 3 as an example for placement of wells in relation to the water table and land surface contour map. Prominent features influencing the location of wells are elevation contours, landfill position, and the nearby river.

Quality data from existing wells frequently have been obtained regularly over a number of years. These wells may serve two important functions for groundwater monitoring, (1) to supply background historical data, which are highly important to form a base for identification and movement of contamination, and (2) to provide a backup system to locate and quantify any contamination reaching the groundwater. Information useful for the monitoring program is

1. Depth of the well and the static water level
2. Depth to intake aquifer and screening inlets
3. Seasonal water level fluctuations
4. Water quality fluctuations (metals and organics)
5. Pump tests to determine discharge capacity

The rating of hydrological and hydrogeographical characteristics as presented earlier in Table 7 includes additional important features, such as:

1. Distance to surface water bodies
2. Distance between wells
3. Depth to karst
4. Depth to bedrock
5. Flooding frequency
6. Drainage patterns and water flows

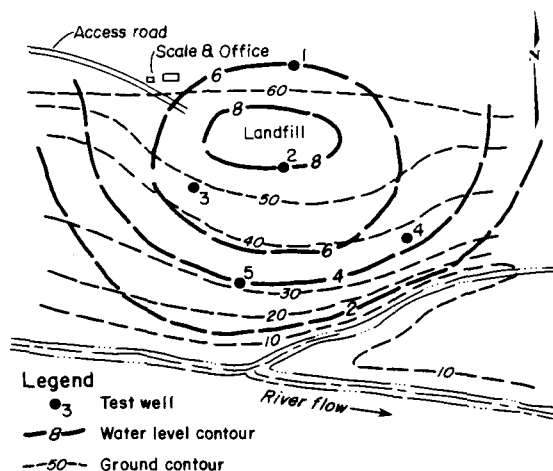


FIGURE 3. The water table and land surface contour map with test well locations. (From Walsh, J., *Process Design Manual: Municipal Sludge Landfills*, EPA-625/1-78-010 and SW-705, Section 7, U.S. Environmental Protection Agency, Washington, D.C., 1978, chap. 7.)

2. Water Quality Monitoring

Water quality is an essential part of surface and groundwater monitoring. An example of the type of information needed is illustrated in Table 7. The legal description locating the wells is highly important. Chemical contents of the waters include soluble salts, calcium, magnesium, sodium chloride, sulfate, bicarbonates, carbonates, fluoride, nitrates, boron, and sodium absorption ratios. Also, pH data are usually available.

Specific analysis of the water, to check for contamination, should include total organic carbon, heavy metals, minor constituents, and trace constituents, as listed, depending on the waste composition. Minor and trace element analyses that can be useful are

Minor constituents (0.001 to 0.1 mg/ℓ)

Antimony	Lead
Aluminum	Lithium
Arsenic	Manganese
Barium	Molybdenum
Bromide	Nickel
Cadmium	Phosphate
Chromium	Rubidium
Cobalt	Selenium
Copper	Titanium
Germanium	Uranium
Iodide	Vanadium
Iron	Zinc

Trace constituents (generally less than 0.001 mg/ℓ)

Beryllium	Silver
Bismuth	Thallium
Cesium	Thorium
Gallium	Tin
Gold	Tungsten
Indium	Zirconium
Lanthanum	Platinum

Table 7
FORM USED FOR ROUTINE WATER ANALYSIS: PRESENTED TO ILLUSTRATE THE KINDS OF DATA
REQUIRED FOR WATER MONITORING OF WELLS BY SOILS, WATER, AND ENGINEERING, UNIVERSITY OF
ARIZONA, TUCSON

THE UNIVERSITY OF ARIZONA
College of Agriculture
Department of Soils, Water and Engineering
Soils, Water and Plant Tissue Testing Lab.
Tucson, Arizona 85721

14

ROUTINE WATER ANALYSIS

COLLECTOR: _____

NAME _____

ADDRESS _____

DATE _____

BILL TO: _____

NAME _____

ADDRESS _____

ZIP _____

PO/Fund No. _____

COMMENTS: _____

20	Sample location		Sample date	Source ^a				Static Well water depth level	Milligrams per liter (mg/ℓ) ^b																
	Sec.	TWP		R	ID	E	W		G	Other (specify)	Lab. No.	EC × 10 ³ (ppm)	Solu salts	pH	Ca	Mg	Na	Cl	SO ₄	HCO ₃	CO ₃	F	N ^c	B	SAR ^d
22																									
23																									
24																									
25																									
26																									
27																									

^a E, effluent; W, well; G, gravity; and O, other (specify).
^b mg/l is approximately equal to ppm.
^c Analyzed as nitrate.
^d Sodium absorption ratio.

Metals which are most frequently a problem are arsenic, beryllium, cadmium, chromium, copper, iron, lead, mercury, selenium, and zinc. Cyanide and asbestos (a mineral) complete the list of those hazardous constituents most often encountered in wastes. They may or may not be essential for plant growth, but, if present in the soil solution in high enough concentration (except asbestos), are absorbed by and toxic to plants.

Soluble organic substances appear to be retained relatively poorly by the soil as compared to most heavy metals. Specific evidence of this may be found for total organic carbon compounds and complexes in MSW landfill leachates:⁹⁻¹¹ for cyanides;¹²⁻¹⁴ for fulvic and humic acids;¹⁵ for phenols;^{16,17} for organic mercury compounds;¹⁸ and for organic phosphorus compounds^{19,20} as well as for TCE and certain chlorinated hydrocarbons. The migration of pesticides through soils is highly variable and depends on the nature of the specific compound involved and the vehicle of transport.²¹⁻²⁹ Therefore organic compounds are difficult to compare with heavy metals in a generalized way. Also, it is unwise to generalize even among organics since there are many exceptions depending largely on concentration and nature of the organic constituent and solvent.

Movement of organic constituents of MSW leachates and of other transport systems may be determined on an "input-output" basis by the soil-column technique in the same manner as for heavy metals. The movement of the many organic substances in MSW leachates, for example, responds similarly to the same soil properties that influence the inorganic constituents or metals just discussed. Soils with the greatest amount of clay retained the greatest amount of organic carbon constituents, other factors being equal. Sandy soils, such as Kalkaska sand, Wagram sand, and Riverbottom alluvium, for example, retain the TOC constituents of MSW leachates poorly. Breakthrough for sandy soils often is evident in less than one pore-volume displacement. Retention of organic carbon (TOC) constituents by seven soils was found to be highly correlated (at the 1% level) with content of clay and surface area per unit weight of soil.^{9,30,31} No effort was made in this study to identify relative retention values for the specific organic compounds present in the solid waste leachate; only the total amount of organic C was evaluated.

The "free" iron oxide or hydrous oxides of iron also appear to react with organic compounds and, thereby, aid in precipitation and retention. The Oxisol, Molokai clay, which has the highest level of "free" iron oxides also retains organic carbon constituents to a greater extent than other soils.^{9,30,31}

Organic solvents, on the other hand, differ considerably in behavior in soils than MSW-leachate organics and appear to move through soil more in relationship to their effects on soil permeability than any other factor.^{32,33} Surface waters in and near disposal facilities usually need routine monitoring. The nearness of the facility to the surface water channels and drainageways will determine the frequency of the monitoring program. Detailed sampling of MSW landfill leachates and other surface waters is presented in a U.S. Environmental Protection Agency (EPA) publication.⁸ Water sample size and sample preservation vary widely depending on the constituent to be measured (Table 8).

F. Soil Erosion

Climatic data are necessary for soil and water erosion control practices. Annual amount and distribution of rainfall and the seasonal temperature of the disposal site are important climatic factors that should be considered in the design of a land application system. These data are usually available from nearby weather stations and a review of historical climate data. These data must then be modified to conform the microclimate at the site. The solute concentration of the leachate from solid waste landfills, for example, depends on the amount of water that passes through the disposal site. Freezing and thawing also influence constituent solubility and migration rates through soil. Wind velocities and prevailing seasonal directions affect (or cause) water evaporation from the soil plant system.

Table 8
SAMPLE SIZE AND SAMPLE PRESERVATION FOR WATER ANALYSES^a

Measurement	Vol reg (mℓ)	Container	Perservation	Holding time ^f	Standard method number ^g
Acidity	100	P,G ^b	Cool, 4°C	24 hr	402
Alkalinity	100	P,G	Cool, 4°C	24 hr	403
Arsenic	100	P,G	HNO ₃ to pH <2	6 months	404
BOD	1000	P,G	Cool, 4°C	6 hr ^c	507
Bromide	100	P,G	Cool, 4°C	24 hr	406
COD	50	P,G	H ₂ SO ₄ to pH <2	7 days	508
Chloride	50	P,G	None required	7 days	408
Chlorine required	50	P,G	Cool, 4°C	24 hr	412
Color	50	P,G	Cool, 4°C	24 hr	204
Cyanides	500	P,G	Cool, 4°C	24 hr	413
			NaOH to pH 12		
Dissolved oxygen					402
Probe	300	G only	Det. on site	None	
Winkler	300	G only	Fix. on site	None	
Fluoride	300	P,G	Cool, 4°C	7 days	414
Hardness	100	P,G	Cool, 4°C	7 days	309
Iodine	100	P,G	Cool, 4°C	24 hr	416
MBAS	250	P,G	Cool, 4°C	24 hr	512
Metals					301
Dissolved	200	P,G	Filter on site	6 months	
			HNO ₃ to pH <2		
Suspended Total	100		Filter on site	6 months	
			HNO ₃ to pH <2		
Mercury					315
Dissolved	100	P,G	Filter HNO ₃ to pH <2	38 days (glass) 13 days (hard plastic)	
Total	100	P,G	HNO ₃ to pH <2	38 days (glass) 13 days (hard plastic)	
Nitrogen					417
Ammonia	400	P,G	Cool, 4°C	24 hr ^d	418
			H ₂ SO ₄ to pH <2		
Kjeldahl	500	P,G	Cool, 4°C	24 hr ^d	421
Nitrite	100	P,G	H ₂ SO ₄ to pH <2	24 hr ^d	419
			Cool, 4°C		
Nitrate	50	P,G	H ₂ SO ₄ to pH <2	24 hr ^d	420
			Cool, 4°C		
NTA	50	P,G	Cool, 4°C	24 hr	—
Oil and grease	1000	G only	Cool, 4°C	24 hr	502
			H ₂ SO ₄ to pH <2		
Organic carbon	25	P,G	Cool, 4°C	24 hr	505
			H ₂ SO ₄ to pH <2		
pH	25	P,G	Cool, 4°C	6 hr ^c	424
			Det. on site		
Phenolics	500	G only	Cool, 4°C	24 hr	574
			H ₃ PO ₄ to pH <4		
			1.0 g CuSO ₄		
Phosphorus Ortho- phosphate, dissolved	50	P,G	Filter on site	24 hr ^d	425
			Cool, 4°C		
Hydrolyzable	50	P,G	Cool, 4°C	24 hr ^d	
Total	50	P,G	H ₂ SO ₄ to pH <2	24 hr ^d	
			Cool, 4°C		
Total, dissolved	50	P,G	Filter on site	24 hr ^d	
			Cool, 4°C		

Table 8 (continued)
SAMPLE SIZE AND SAMPLE PRESERVATION FOR WATER ANALYSES^a

Measurement	Vol reg (mℓ)	Container	Perservation	Holding time ^f	Standard method number ^g
Residue Filterable	100	P,G	Cool, 4°C	7 days	208
Nonfilterable	100	P,G	Cool, 4°C	7 days	
Total	100	P,G	Cool, 4°C	7 days	
Volatile	100	P,G	Cool, 4°C	7 days	
Settleable matter	1000	P,G	None required	24 hr	208
Selenium	50	P,G	HNO ₃ to pH <2	6 months	318
Silica	50	P, only	Cool, 4°C	7 days	426
Specific conductance	100	P,G	Cool, 4°C	24 hr ^c	205
Sulfate	50	P,G	Cool, 4°C	7 days	427
Sulfide	50	P,G	2 mℓ zinc acetate	24 hr	428
Sulfite	50	P,G	Cool, 4°C	24 hr	429
Temperature	1000	P,G	Det. on site	None	212
Threshold odor	200	G only	Cool, 4°C	24 hr	206
Turbidity	100	P,G	Cool, 4°C	7 days	214

^a More specific instructions for preservation and sampling are found with each procedure as detailed in the literature (1). A general discussion on sampling water and industrial wastewater may be found in ASTM, Part 23, p. 72-91 (1973).

^b Plastic or glass.

^c If samples cannot be returned to the laboratory in less than 6 hr and holding time exceeds this limit, the final reported data should indicate the actual holding time.

^d Mercuric chloride may be used as an alternate preservation at a concentration of 40 mg/ℓ, especially if a longer holding time is required. However, the use of mercuric chloride is discouraged whenever possible.

^e If the sample is stabilized by cooling, it should be warmed to 25°C for reading or temperature correction made and results reported at 25°C.

^f It has been shown that samples properly preserved may be held for extended periods beyond the recommended holding time.

^g The numbers in this column refer to the appropriate parts of the "Standard Methods for the Examination of Water and Wastewater, 14th edition, APHA-AWWA-WPCF, 1975.

Methods for evaluating soil erosion induced by the action of water and wind are described in Chapter 4. Monitoring soil erosion primarily involves the control of runoff water. A NPDES permit requires water quality data on runoff, if the facility discharges water into any drainageway or streambed, either directly or indirectly. Acceptable discharge quality must be demonstrated. Analyses must be made as indicated by the permit plus the hazardous constituents of the waste retained, modified, or otherwise managed so that the runoff is brought to compare with the historic groundwater quality. The runoff water quality must continue to be acceptable during postclosure periods.

Soil erosion prediction can involve the field-oriented Universal Soil Loss Equation (USLE) of Wischmeier and Smith³⁴ and is applicable to any exposed soil surface. Some design instructions for erosion control are listed for landfills as examples:

1. Insist the site located on soils with low erodability factor, K, in the USLE equation.
2. If the closure soil has a high erodability factor, bring in better soil or use some kind of protective management.
3. Control slope length, L, and slope steepness, S, in the design to accomodate the type of soil available. If the final height of the cover exceeds 5 feet from the base, arrange for contour ridges for water control and drain away the water by grassed waterways.

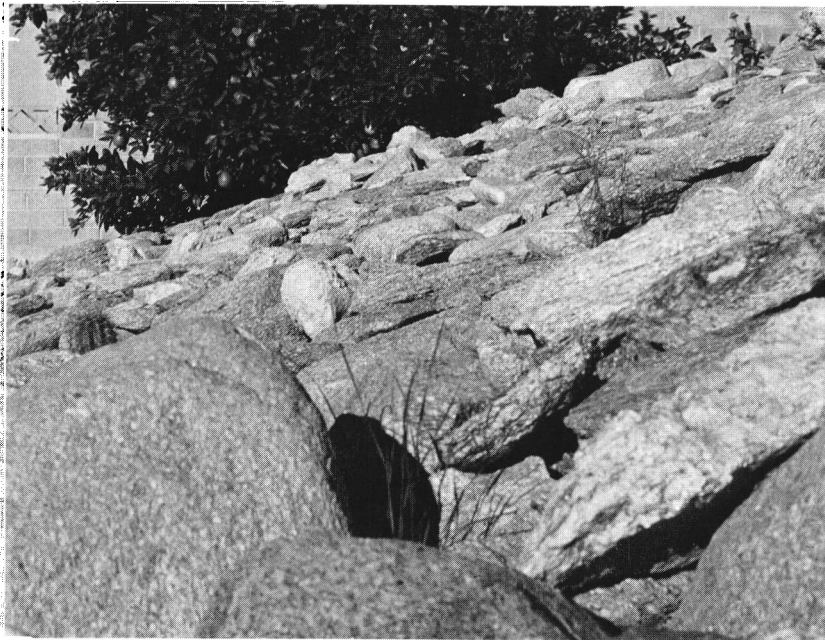


FIGURE 4. Rock mulch of variable sizes and textures of rock stabilize the soil against wind and rain erosion and add interest and beauty to any natural covering. (From Fuller, W. H., Rock mulch is rediscovered, *Prog. Agric. Ariz.*, 15, 8, 1973. With permission.)

4. Establish adopted vegetation in as dense a seeding as practicable and maintain continuous cover after closing.
5. Mulch with suitable organic residues such as straw, farm animal waste, or compost suited to the climatic area. Stone and gravel also provide good mulching properties for holding the soil against wind and rain erosion (Figure 4).
6. Plan for a future long-term maintenance erosion-control program following closure, using the talent of the USDA Soil Conservation Service aid programs.

IV. CLOSURE

A. General Criteria

The site closure procedure should be designated in the first stage of the site design plan with its roots well back into the site selection decision. The general criteria must be considered before planning the final facility use. The final use planned for the facility should have been considered long before at the early planning stage. The cost of proper closure can be reduced by incorporating the final site closure plans into the original design. The closure must be acceptable to the community and not deteriorate the original land values. Some states require both monitoring and maintenance of the facility by the operator and owner for a period of time (years) after the facility closure.⁷ Thus, a desirable closure procedure can perhaps best be secured by giving consideration to and conducting work on the closure concurrently with the landfill, that is, simultaneously with the operation of filling. Also, consideration should be given to data collection as suggested in Table 9 for monitoring during closure and post closure as reported from six different sites.⁴¹

Table 9
MONITORING PROGRAM DURING OPERATION, CLOSURE, AND POSTCLOSURE

Purpose		Sampling frequency	Number of samples		Parameters
Waste	Quality change	Quarterly if continuous stream, each batch if intermittent generation	1		Rate and capacity limiting constituent, plus those within 25% of being limiting
Soil in the zone of incorporation	Determine degradation pH, nutrients, and rate and capacity limiting constituents	Load design life: Frequency of sampling during operation and closure:	Load design life:	1 sample per: ^a	Rate and capacity limiting constituent, those within 25% of being limiting, pH, nutrients, and residual organics
		<2 years 2—10 years >10 years	<2 years 2—10 years >10 years	0.5 ha 2.0 ha 2.0 ha	
Soil below the zone of incorporation	To determine movement of metals	Load design life: Frequency of sampling during operation and closure:	Load design life:	1 sample per:	Metals that limit the loading capacity, those within 25% of being limiting, plus slowly mobile organics
		<2 years 2—10 years >10 years Annually or at harvests	<2 years 2—10 years >10 years	0.5 ha 2.0 ha 4.0 ha	
Vegetation	Phytotoxic and transmitted constituents and food chain hazards	Annually or at harvests	Load design life:	1 sample per:	Metals nutrients if needed for diagnosis
Runoff water	Soluble or suspended constituents	As required for NPDES permit	Life:		
		Postclosure: $\frac{1}{2}$, 1, 2, 4, 8, 16, and 30 years after closure	<2 years 2—10 years >10 years	0.5 ha 2.0 ha 4.0 ha	
Unsaturated zone water	Determine mobile constituents	Quarterly during operation and closure; preferably following leachate generating	As permit requires, or one	1 sample per:	Discharge permit or background parameters plus organics
Groundwater	Determine mobile constituents	Quarterly during operation and closure; preferably following leachate generating	Load design life:		
		Semiannually during operation and closure; postclosure, $\frac{1}{2}$, 1, 2, 4, 8, 16, and 30 years following closure	<2 years 2—10 years >10 years 1 upgradient and 3 downgradient	0.5 ha 2.0 ha 4.0 ha	

^a Composite of six locations.

From Brown, K. W. and Associates, Inc., Hazardous Waste Land Treatment, EPA-SW-874, U.S. Environmental Protection Agency, 1983, 974.

B. Burials

A most effective closure procedure for landfills has been suggested by Walsh;⁷

Procedures for Site Closure

1. No sludge should be left exposed. Trenches and lifts should be sufficiently covered. If trenches and lifts are unstable, they should be well marked using drums or wooden barricades.
2. Although the rate of settling varies, maximum settlement will occur within the first year of landfilling. Accordingly, sufficient time should be allowed for the area to settle. As necessary, the area should be regraded to account for settlement.
3. After maximum settlement has occurred, the area should be regraded to ensure proper drainage. Depressions and cracks should be filled using on-site or borrowed soil. Bulldozers and/or graders are normally used for spreading and grading the soil.
4. Add 0.3 to 1.0 m (1 to 3 ft) of final cover as needed. This cover may consist of topsoil which was stripped and stockpiled prior to commencing the landfilling operation. Soil that is deficient in organics (e.g., sandy soil) may require a mixture of sludge at a ratio of 5:1 to 10:1.
5. Check sediment and erosion controls and modify according to any change in grade.
6. Construction of small structures (picnic tables, shelters, etc.) may be undertaken in accordance with specifications in the final site use plan.
7. Disassemble temporary structures and receiving areas not required for final site use.
8. Hydroseed denuded areas with the appropriate mixture of grasses. Climate and final site use are a major factor in determining the type of grass and vegetation selected.
9. Outline a timetable to ensure that the following features are inspected at regular intervals:
 - Settlement, cover soil integrity, and need for grading
 - Buffers and vegetation
 - Sediment and erosion control facilities
 - Fencing
 - Leachate and gas controls
 - Integrity of final site use facility
 - Vandalism
 - Monitoring

C. Encapsulations

Closure for encapsulations may follow procedures similar to those of landfills if the encapsulation materials or container is very durable and capable of withstanding soil burial for many years. The surface contours may then be made to conform with the existing off-site topography. Where limestone, gypsum, sand, and gravel have been used as fillers surrounding the encapsulated waste, allowance must be provided for settling and long term maintenance of erosion control methods for the soil surface.

D. Well Injections

In general, closure of well injection should offer the fewest problems of all the closure methods. The most important closure procedure involves returning the land surrounding the injection, as well as the injection well, to a condition as nearly identical to the original as possible. Gas problems should be anticipated, and designs established to minimize hazardous effects from gas and to control its evolution into the atmosphere.

E. Land Treatment/Utilization

The main object of closure procedures for the land treatment area is to get the soil back into plant production as quickly as possible. Some of the means for doing this are as follows:

1. Fertilize with N, P, K, if needed.
2. Apply soil conditioners to improve the physical properties as necessary.
3. Adjust the soil pH to optimum for the climatic zone.
4. In arid or dry lands, irrigate if the moisture is limiting for maximum biodegradation.
5. Cultivate to enhance biodegradation should organic residues or toxic organics remain.
6. Mulch if wind and water erosion threaten.
7. Finally, establish vegetative growth and protective cover as soon as practical.

The final surface should conform as nearly as possible with the surrounding topography, unless the original land contours are too severe and modification lends a more pleasing appearance to the landscape. Where only a few hectares of land are involved in the land treatment and biodegradation is very slow, layering of good soil may vary the length of time when revegetation can be started. This is expensive and most often not practical except where landfill, lagoons, or evaporated impoundments once existed.³⁵

Large areas of land treatment that will not permit establishment of vegetation because of the presence of inhibiting or toxic residues may sometimes be improved by deep plowing to bring agronomic quality soil to the surface and dilute the biologically inhibiting substances with good soil. The main objective is revegetation which in itself is a pollution control practice. Generally, any vegetation is better than none even though it may be of such poor quality and of no economic value. Plowing under of even a weed patch can add valuable organic matter to the soil, enhance microbial activity, hasten biodegradation of growth-inhibiting substances from remnants of waste disposal, and prepare the way for the establishment of a more permanent vegetation.

Discharge of water from the treatment area as runoff after the closure is not permitted (unless approved) until the quality meets the permit requirement. Thus, collection, treatment, and on-site disposal must be continued as before closure. Acceptability of runoff water for "free" discharge from the treatment land is based on the quality of water samples taken at regular periods of time, usually once each month. Isolated samples taken indiscriminantly are not suitable for determining quality trends, which can vary considerably because of season climatic differences and differences in irrigation practices for arid and semiarid lands.

Again, as with landfills, the unsaturated and groundwater monitoring must be continued after closure. Sometimes this may require periodic sampling over many years.³⁶ The importance of site selection, suitable soils, and land features cannot be overemphasized as they influence the need for monitoring pollution movement to groundwaters.³⁷⁻⁴⁰

After closure, crop monitoring for evaluating contaminant absorption and uptake (e.g., heavy metals and toxic organic) must be a part of the closure responsibility. The presence of excessive pollutants in the crop parts may require decontamination designs. Several options are available as described in Chapters 1 and 5.

REFERENCES

1. **Ryan, J. R. and Loehr, R. C.**, Site Selection Methodology for the Land Treatment of Wastewaters, (CRREL) Special Rep., No. 81-28, U.S. Army Corps of Engineers, Hanover, N.H., 1981, 16.
2. **Berdanier, C. R., Jr.**, The role of soils in waste management, in *Agricultural Waste Management Field Manual*, Soil Conservation Service, U.S. Department of Agriculture, Washington, D.C., 1975, chap. 5.
3. **Blakeslee, P. A.**, Site monitoring considerations, in *Applications of Sludges and Wastewaters to Agricultural Land*, Knezek, B. D. and Miller, R. H., Eds., EPA-WH-546, U.S. Environmental Protection Agency, OWPO, Washington, D.C., 1978, chaps. 9 and 11.
4. **Erelenbach, W. E.**, A systematic approach to monitoring trends in the quality of surface waters, in *Establishment of Water Quality Programs*, American Water Resources Association, Minneapolis, 1978, 7.
5. **Fuller, W. H.**, Premonitoring waste disposal sites, in *Establishment of Water Quality Monitoring Programs*, Everett, L. G. and Schmidt, K. D., Ed., Am. Water Resour. Assoc. Symp. Proc., American Water Resources Association, Minneapolis, 1978, 85.
6. U.S. Environmental Protection Agency, Use of Water Balance Method for Predicting Leachate Generation from Solid Waste Disposal Sites, EPA/530/SW-168, U.S. Environmental Protection Agency, 1975, 40.
7. **Walsh, J.**, Process Design Manual: Municipal Sludge Landfills, U.S. EPA-625/1-78-010 and SW-705, Section 7, U.S. Environmental Protection Agency, Washington, D.C., 1978, chap. 7.
8. U.S. Environmental Protection Agency, *Procedures Manual for Groundwater Monitoring at Solid Waste Disposal Facilities*, EPA/530/SW-611, U.S. Environmental Protection Agency, Washington, D.C., 1977, chap. 1.
9. **Fuller, W. H., Amoozegar-Fard, A., Niebla, E. E., and Boyle, M.**, Influence of leachate quality on soil attenuation of metals in Proc. 6th Annu. Res. Symp., Shultz, D., Ed., EPA-600/9-80-010, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1980, 108.
10. **Fuller, W. H. and Alesii, B. A.**, Behavior of municipal waste leachate. II. In soil, *Environ. Sci. Health*, A14, 559, 1979.
11. **Griffin, R. A., Au, A. K., and Frost, R. R.**, Effect of pH adsorption of chromium for landfill-leachate by clay minerals, *J. Environ. Sci. Health*, Part A, 431, 1977.
12. **Alesii, B. A., Fuller, W. H., and Boyle, M.**, Effect of leachate flow rate on metal migration through soil, *J. Environ. Qual.*, 9, 199, 1980.
13. **Alesii, B. A. and Fuller, W. H.**, The mobility of three cyanide forms in soils, in *Residual Management by Land Disposal*, Fuller, W. H., Ed., Proc. Hazardous Waste Res. Symp., EPA-600/9-76-015, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1976, 280.
14. **Fuller, W. H.**, The importance of soil attenuation for leachate control, in *Waste Management Technology, Resource and Energy Recovery*, Proc. 5th Natl. Cong., cosponsored by National Solid Waste Management Assoc. and U.S. Environmental Protection Agency, EPA SW-22P, Washington, D.C., 1977, 297.
15. **Artiola-Fortuny, J. and Fuller, W. H.**, Humic substances in landfill leachates. I. Humic acid extraction and identification, *J. Environ. Qual.*, 11, 663, 1982.
16. **Artiola-Fortuny, J. and Fuller, W. H.**, Phenols in municipal solid waste leachates and their attenuation by clay soils, *Soil Sci.*, 133, 218, 1982.
17. **Artiola-Fortuny, J. and Fuller, W. H.**, Absorption of some monohydroxybenzene derivatives by soils, *Soil Sci.*, 133, 18, 1982.
18. **Niebla, E. E., Korte, N. E., Alesii, A. B., and Fuller, W. H.**, Effect of municipal landfill leachate on mercury through soils, *Water Air Soil Pollut.*, 3, 399, 1976.
19. **Hannapel, R. J., Fuller, W. H., Bosma, S., and Bullock, J. S.**, Phosphorus movement in a calcareous soil. I. Predominance of organic forms of phosphorus in phosphorus movement, *Soil Sci.*, 97, 350, 1964.
20. **Hannapel, R. J., Fuller, W. H., and Fox, R. H.**, Phosphorus movement in a calcareous soil. II. Soil microbial activity and organic phosphorus movement, *Soil Sci.*, 97, 421, 1964.
21. **Griffin, R. A. and Chou, S. F. J.**, Disposal and removal of halogenated hydrocarbons in soil, in Proc. 6th Annu. Res. Symp., Shultz, D., Ed., EPA-600/9-80-010, U.S. Environmental Protection Agency, MERL, Cincinnati, OH, 1980, 82.
22. **Lee, M., Griffin, R. A., Miller, M. L., and Chian, E. S. K.**, Absorption of water-soluble and polychlorinated biphenyl Aroclor 1242 and used capacitor fluid by soil materials and coal chars, *J. Environ. Sci. Health*, A14, 415, 1979.
23. **Leis, W. W., Beers, W. F., Davidson, J. M., and Knowles, G. D.**, Migration of PCBs by ground-water transport — a case study of twelve landfills and dredge disposal sites, in the upper Hudson Valley, New York, Conf. Applied Research and Practice on Municipal and Industrial Waste, Madison, Wis., 1978, 539.
24. **Fields, T. and Lindsay, W. A.**, Landfill Disposal of Hazardous Wastes: A Review of Literature and Known Approaches, U.S. EPA Rep. SW-165, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio, 1975, 36.

25. **Katan, J. and Lichtinstein, E. P.**, Mechanisms of production of soilbound residues of ¹⁴C Parathion by microorganisms, *J. Agric. Food Chem.*, 25, 1404, 1977.
26. **Kay, B. D. and Elrick, D. E.**, Absorption and movement of lindane in soils, *Soil Sci.*, 104, 314, 1967.
27. **Huggenberger, F., Letey, J., and Farmer, W. J.**, Observed and calculated distribution of lindane in soil columns as influenced by water movement, *Soil Sci. Soc. Am. Proc.*, 26, 544, 1972.
28. **Goring, C. I. A. and Hamaker, J. W.**, *Organic Chemicals in Soil Environment*, 1, II, Mercel Dekker, New York,
29. **Davidson, J. M., Rao, P. S. C., and Ou, L-T.**, Movement and biological degradation of large concentrations of selected pesticides in soils, in *Disposal of Hazardous Wastes*, Shultz, D., Ed., Proc. 6th Annu. Res. Symp., EPA-600/9-80-010, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1980, 93.
30. **Fuller, W. H., Amoozegar-Fard, A., and Carter, G. E.**, Predicting movement of selected metals in soils: application to disposal problems, in *Municipal Solid Waste: Land Disposal*, Proc. 5th Annu. Res. Symp., Shultz, D., Ed., EPA-600/9-79-023a, U.S. Environmental Protection Agency, MERL, Cincinnati, Ohio 1979, 358.
31. **Fuller, W. H., Amoozegar-Fard, A., Niebla, E., and Boyle, M.**, Behavior of Cd, Ni, and Zn in single and mixed combinations in landfill leachate, in *Land Disposal: Hazardous Wastes*, Proc. 7th Annu. Res. Symp., Shultz, D., Ed., EPA-600/9-81-026, U.S. Environmental Protection Agency, MERL, Cincinnati, 1981, 18.
32. **Wilson, J. T., Enfield, C. G., Dunlap, W. J., Cosby, R. L., Foster, D. A., and Baskins, L. B.**, Transport and fate of selected organic pollutants in a sandy soil, *J. Environ. Qual.*, 10, 501, 1981.
33. **Brown, K. W. and Associates, Inc.**, Hazardous Waste Land Treatment, EPA-SW-874, U.S. Environmental Protection Agency, OWWM, 1983, 974.
34. **Wischmeier, W. H. and Smith, D. D.**, Predicting Rainfall Erosion Losses — A Guide to Conservation Planning, Agric. Handbo. 537, U.S. Department of Agriculture, 1978, 10.
35. **Blakeslee, P. A.**, Monitoring considerations for municipal wastewater effluent and sludge application to land, in *Recycling Municipal Sludge and Effluent on Land*, Proc. Joint Conf., Pub. National Assoc. State Univ. and Land-Grant Coll., Washington, D.C., 1973, 183.
36. **Todd, D. K. and McNulty, D. E.**, *Polluted Groundwater, A Reivew of the Significant Literature*, Water Information Center, Inc., Port Washington, N.Y. 1975, 1.
37. **Moser, M. A., Ryan, J. R., and Loehr, R. C.**, Assessing soil series suitability for the land treatment of wastewaters, Paper No. NAR 80-207, 1980 Annu. Meet. North Atlantic Region, American Society Agric. Engin., St. Joseph, Mich. 1980, 1.
38. **Metcalf and Eddy, Inc.**, Feasability of Land Treatment of Wastewaters in the Metropolitan Region of Nashville, Tennessee, Urban Study Area, Nashville District, Corps of Engineers, Federal Courthouse, Nashville, Tenn., 1978, 1.
39. **LeGrand, H. E.**, Systems for evaluation of contamination potential of some waste disposal sites, *J. Am. Water Works Assoc.*, 56, 959, 1969.
40. **Phillips, C. R.**, Development of a soil-waste interaction matrix for assessing land disposal of industrial wastes, *Water Res.*, 11, 959, 1977.

Appendixes



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

APPENDIX A

USDA AND USCS PARTICLE CLASSIFICATIONS

The USDA classification which may be compared most directly with the soil types in the USCS system is soil texture (distribution of grain or particle size) and associated modifiers such as gravelly, mucky, diatomaceous, and micaceous. The size ranges for the USDA and the USCS particle designations (e.g., sand and gravel) are listed in Table 1. The soil texture (USDA — sandy loam, silt loam, etc.) or the soil type (USCS — GC, clayey gravel; SC, clayey sand, etc.) is based on the relative amounts of different-sized particles in a soil. The USDA system for classifying soil texture is compared in Volume I, Chapter 1, Figures 25 and 26; an abbreviated description for the USCS classification is listed in Table 2. Correlation of the USCS and USDA systems on the basis of texture is presented in Tables 2 and 3. These correlations are not precise because texture is a major criterion in the USCS, while texture is a minor criterion in the USDA system. A soil of a given texture can be classified into only a limited number of the 15 USCS soil types, while in the USDA system, soils of the same texture may be found in many of the 10 orders and 43 suborders because of differences in their chemical properties or the climatic areas in which they are located.

Table 1
USDA AND USCS PARTICLE SIZES

USDA		USCS	
Particle	Size range (mm)	Particle	Size range (mm)
Cobbles	76.2—254.0	Cobbles	>76.2
Gravel	2.0—76.2	Gravel	4.76—76.2
Coarse gravel	12.7—76.2	Coarse gravel	19.1—76.2
Fine gravel	2.0—12.7	Fine gravel	4.76—19.1
Sand	0.05—2.0	Sand	0.074—4.76
Very coarse sand	1.0—2.0		
Coarse sand	0.5—1.0	Coarse sand	2.0—4.76
Medium sand	0.25—0.5	Medium sand	0.42—2.0
Fine sand	0.1—0.25	Fine sand	0.074—0.42
Very fine sand	0.05—0.1		
Silt	0.002—0.05	Fines ^a	<0.074
Clay	<0.002	(silt and clay)	

^a USCS silt and clay designations are determined by response of the soil to manipulation at various water contents rather than by measurement of size.

From Fuller W. H., *CRC Crit. Rev. Environ. Control*, 9, 261, 1980. With permission.

Table 2
MAJOR DIVISIONS, SOIL TYPE SYMBOLS, AND TYPE DESCRIPTIONS
FOR THE UNIFIED SOIL CLASSIFICATION SYSTEM (USCS)

Major divisions	Symbol	Description
Coarse-grained soils — More than half of material is larger than No. 200 sieve size		
Gravels — More than half of coarse fraction is larger than No. 4 sieve size.		
Clean gravel — little or no fines	GW	Well graded gravels, gravel-sand mixtures, little or no fines
	GP	Poorly graded gravels or gravel-sand mixtures, little or no fines
Gravels with fines (appreciable fines)	GM	Silty gravels, gravel-sand-silt mixture
	GC	Clayey gravels, gravel-sand-clay mixtures
Sands — More than half of coarse fraction is smaller than No. 4 sieve size.		
Clean sands (little or no fines)	SW	Well-graded sands, gravelly sands, little or no fines
	SP	Poorly graded sands or gravelly sands, little or no fines
Sands with fines (appreciable fines)	SM	Silty sands, sand-silt mixtures
	SC	Clayey sands, sand-clay mixtures
Fine-grained soils — More than half of material is smaller than No. 200 sieve size		
Silts and clays — liquid limit is less than 50	ML	Inorganic silts and very fine sands, silty or clayey fine sands or clayey silts with slight plasticity
	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
	OL	Organic silts and organic silty clays of low plasticity
Silts and clays — liquid limit is greater than 50	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts
	CH	Inorganic clays of high plasticity fat clays
	OH	Organic clays of medium to high plasticity, organic silts
Highly organic soils	Pt	Peat and other highly organic soils

Notes: ML includes rock flour. The No. 4 sieve opening is 4.76 mm (0.187 in.); the No. 200 sieve opening is 0.074 mm (0.0029 in.)

From Fuller, W. H., *CRC Crit. Rev. Environ. Control*, 9, 262, 1980. With permission.

Table 3
CORRESPONDING USCS AND USDA SOIL CLASSIFICATIONS

USCS soil types	Corresponding USDA soil textures
1. GW	Same as GP — gradation of gravel sizes not a criterion
2. GP	Gravel, very gravelly ^a sand less than 5% by weight silt and clay
3. GM	Very gravelly ^a sandy loam, very gravelly ^a loamy sand, very gravelly ^a silt loam, and very gravelly ^a loam ^b
4. CG	Very gravelly clay loam, very gravelly sandy clay loam, very gravelly silty clay loam, very gravelly silty clay, very gravelly clay ^b
5. SW	Same — gradation of sand size not a criterion
6. SP	Coarse to fine sand; gravelly sand ^c (less than 20% very fine sand)
7. SM	Loamy sands and sandy loams (with coarse to fine sand), very fine sand; gravelly loam sand ^c and gravelly sandy loam ^c
8. SC	Sandy clay loams and sandy clays (with coarse to fine sands); gravelly sandy clay loams and gravelly sandy clays ^c
9. ML	Silt, silt loam, loam very fine sandy loam ^d
10. CL	Silty clay loam, clay loam, sandy clays with <50% sand ^d
11. OL	Mucky silt loam, mucky loam, mucky silty clay loam, mucky clay loam
12. MH	Highly micaceous or diatomaceous silts, silt loams — highly elastic
13. CH	Silty clay and clay ^d
14. OH	Mucky silty clay
15. PT	Muck and peats

^a Also includes cobbly, channery, and shaly.

^b Also includes all of textures with gravelly modifiers where <1/2 of total held on No. 200 sieve is of gravel size.

^c Gravelly textures included if less than 1/2 of total held on No. 200 sieve is of gravel size.

^d Also includes all of these textures with gravelly modifiers wither <1/2 of the total soil passes the No. 200 sieve.

From Fuller, W. H., *CRC Crit. Rev. Environ. Control*, 9, 263, 1980. With permission.

APPENDIX B

ENGLISH - SI
CONVERSION CONSTANTS

Length	in.	ft	yd	mi	cm	m	km
1 in.	1	0.083	0.027	—	2.54	—	—
1 ft	12	1	0.333	—	30.48	0.305	—
1 yd	36	3	1	—	91.44	0.914	—
1 mi (statute)	—	5280	1760	1	—	1609	1.61
1 cm	0.394	0.033	0.011	—	1	0.1	—
1 m	39.37	3.281	1.094	—	100	1	0.001
1 km	—	3281	1094	0.621	—	1,000	1
Areas	in. ²	ft ²	yd ²	acre	cm ²	m ²	ha
1 in. ²	1	0.007	—	—	6.45	0.00064	—
1 ft ²	144	1	0.1111	—	—	0.0929	—
1 yd ²	1,296	9	1	—	—	0.8361	—
1 acre	—	43,560	4,840	1	—	4,047	0.405
1 cm ²	0.155	—	—	—	1	0.0001	—
1 m ²	1550	10.76	1.20	—	10,000	1	0.0001
1 ha	—	107,650	11,961	2.47	—	10,000	1
Volume	in. ³	ft ³	Am. gal	ℓ	m ³	ac—ft	ha—m
1 in. ³	1	—	0.0043	0.0164	—	—	—
1 ft ³	1,728	1	7.481	28.32	0.0283	—	—
1 Am. gal	231	0.134	1	3.785	0.0038	—	—
1 ℓ	61.02	0.0353	0.2642	1	0.001	—	—
1 m ³	61,022	35.31	264.2	1,000	1	0.00081	0.0001
1 ac—ft	—	43,560	325,872	—	1,233.4	1	0.1233
1 ha—m	—	353,198	—	10 × 10 ⁶	10,000	8.108	1

Note: 1 yd³ = 0.765 m³; 1 m³ = 1.308 yd³.

ABBREVIATIONS, SIGNS, AND SYMBOLS

Abbreviations

AASHO	Old Agricultural Department system for particle sizes (pre-1938)
AEC	Positive charge of anion exchange capacity
API	American Petroleum Institute also used as API separator sludge as waste residue of first centrifuge of refinery waste water
ASC	Anion sorption capacity
BOD	Biological oxygen demand
CEC	Total cation exchange capacity
CEC _c	Negative charge of cation exchange capacity
CEC _v	Variable charge of cation exchange capacity
CFU	Colony forming units
CLAY	Percent clay
CLC	Loading capacity limiting constant
COD	Chemical oxygen demand
DL	Design life
DLR	Design loading rate
EC	Electrical conductivity
Eh	Reduction/oxidation factor
EPA	U.S. Environmental Protection Agency
erf (μ)	Error Function of argument μ
erfc (μ)	Complementary error function of argument μ
esu	Electro static unit
exp (μ)	Exponential function of argument μ
FeO	Free iron oxide (only in equations)
ISW	Industrial solid waste
LT	Land treatment
MeV	Million electron volts
MSW	Municipal solid waste
ppb	Parts per billion
pH	A measure of hydrogen ion activity [H^+] (i.e., $pH = -\log [H^+]$)
ppm	Parts per million
PV	Pore volume (units L^3)
PVC	Polyvinyl chloride
PVD	Pore volume displacement
red/ox	Reduction/oxidation ratio
s	Second
SALTS	Soluble salts
SAR	Sodium-absorption ratio
SLF	Sanitary landfill
SSD	Sum of square of differences
SAND	Percent sand
SILT	Percent silt
TC	Total carbon
TIC	Total inorganic carbon
TOC	Total organic carbon
TR	Toxicity reduction
USCS	Unified Soil Classification System
USDA	United States Department of Agriculture
WHC	Water holding capacity

Symbols and Signs

General

A	Delay factor
c	Concentration of the element in soil water (M/L^3)
c_o	Concentration of the element in liquid entering the soil profile (or column)(units M/L^3)
c/c_o	Relative concentration (unitless)
D	Apparent diffusion coefficient (also known as dispersion coefficient)(units L^2/T)
D_c	Modified apparent diffusion coefficient (units L^2/T)
I_0	Modified Bessel function of the first kind of zero order
I_1	Modified Bessel function of the first kind of first order
K_1	Forward reaction term (units $1/T$)
K_2	Backward reaction term (units $1/T$)
n	Amounts of element adsorbed per unit volume of soil (units M/L^3)
R_n	Error of integration by Gauss' formula
r^2	Coefficient of determination
t	Time (units)
V_i	Velocity of relative concentration i (units L/T)
v	Pore water velocity, convective velocity (units L/T)
z	Depth in profile (units L)
α	Fractional pore volume of soil (units L^3/L^3)
ρ_b	Bulk density of soil (units g/cm^3)
ρ_p	Particle density of soil (units g/cm^3)

Texture of Soils

c	clay, $< 2 \mu m$ size particles
c l	clay loam
s	sand
s l	sandy loam
l	loam
si	silt
si l	silt loam
si c l	silty clay loam

Units

a	acre
cfs	cubic feet per second
d	day
dyne	unit of force, in cgs ($g \text{ cm/s}^2$)
eq	equivalent
meq	milliequivalent
meq/100	milliequivalent per 100 grams
g	gram
kg	kilogram (10^3 grams)
lb	pound
mg	milligram (10^{-3} grams)
μg	microgram (10^{-6} grams)

Symbols and Signs

Units (Continued)

h	hour
ℓ	liter (0.946 quarts)
mℓ	milliliter (1 mℓ = 1 cm ³ = 1 c.c.)
m	meter (39.4 inches)
km	kilometer (0.621 miles)
cm	centimeter (0.394 inches)
mm	millimeter
mhos	reciprocal of ohms
mmhos	millimhos
μmhos	micromhos
μmhos/cm	micromhos/cm (measure of EC)
μ	micron
gal	gallon
gal/min	gallon/minute
lb	pound
min	minute
pvd	pore volume displacement
s	second
t	metric ton
t/ha	metric tons/hectare
T	English tons
T/a	English tons/acre

Elements

Ag	silver
Al	aluminum
As	arsenic
Au	gold
B	boron
Be	beryllium
C	carbon
Ca	calcium
Cd	cadmium
Cl	chloride
Co	cobalt
Cr	chromium
Cu	copper
Fe	iron
Fe ⁺⁺ (FeII)	ferrous
Fe ⁺⁺⁺ (FeIII)	ferric
H	hydrogen
Hg	mercury
I	iodine
K	potassium
Mg	magnesium
Mn	manganese
Mo	molybdenum

Symbols and Signs
Elements (Continued)

N	nitrogen
Ni	nickel
O	oxygen
P	phosphorus
Pb	lead
Se	selenium
Sn	tin
Si	silicon
Ti	titanium
Zr	zircon
Zn	zinc

Chemicals

CO ₂	carbon dioxide
CO ₃	carbonate
HCO ₃	bicarbonate
NH ₄	ammonium
NO ₂	nitrite
NO ₃	nitrate
PO ₄	phosphate
SO ₄	sulfate

Index



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

INDEX

A

Absorption
 barrier to, 28
 gases, 64
 liner capacity for, 42
 Acceptability of odors, 68
 Acetic acid, 162, 164, 184
 Acetoin, 72
 Acetylene, 72
 Acid rain, 69
 Acids, see also specific acids, 146, 184—185
 aqueous, 105—106
 concentration effects of, 183—184
 effect of on soils, 143
 inorganic, 152—162
 nitric acid, 156—158
 phosphoric acid, 159, 161—162
 sulfuric acid, 158—160
 organic, 162—164
 strong aqueous, 105—106
 strong inorganic, 152—162
 nitric acid, 156—158
 phosphoric acid, 159, 161—162
 sulfuric acid, 158—160
 Actinomycetes, 87
 Acute microbial toxicity and biodegradation, 89—91
 Aerobic equipment, 109
 Aerosols, see also specific aerosols, 59, 68—69
 microorganisms containing, 68
 Agars, 87
 Alcohols, see also specific alcohols, 60
 Aluminum, 79, 86, 151, 169, 179
 Aluminum chloride-iron chloride solution, 151—152
 Anaerobic equipment, 109
 Analyses, see also specific types
 chemical, 85—86
 effluent, 148
 mechanical, 86
 multiple regression, 128—129
 physical, 86
 soil, 28, 148
 statistical, 112
 X-ray, 86, 146
 Anions, 185
 Anoxic equipment, 109
 Anthony sandy loam, see also Reference soils, 114,
 129, 148, 151
 Aquaculture ponds, 54—55
 Aqueous acids, 105—106
 Aqueous inorganic/organic fluids, 104
 Aqueous organic fluids, 104—105
 Aquifers, 4, 13, 64
 Arsenic, 29, 208
 Asbestos, 208
 Assays, 90
 Attenuation
 metals in soil, 79
 pollutants, 42—44

prediction of, 98—99
 soil properties and, 28—29
 Ava silty clay loam, see also Reference soils, 117
Azolla caroliniana (lesser fairy moss), 55

B

Bacteria, 87
 Barriers, 64
 absorption, 28
 Bases, 105—106
 Batch studies, 98—99
 Bentonite clay, 15
 Benzine, 66
 Beryllium, 36, 208
 Bioassays, 90
 Biodegradation
 acute microbial toxicity and, 89—91
 microbial population and, 86—88
 rate of, 5, 79, 81
 Biological oxidation rate in soil filter scrubbers, 72
 Biological oxygen demand (BOD), 46
 Biological treatment ponds, 52
 Bioresistant nut hulls, 15
 BOD, see Biological oxygen demand
 Boron, 159, 172
 Breakthrough curves, 28, 112, 113, 124
 Brightening mix, spent acid wastes, 180—181
 Bulk density of soil, 86, 164
 Burials, see also specific topics, 213
 encapsulation, 25
 landfills, 3—21
 liners for, 42—50
 trenches, 21—22, 25
 Burning, 3
 open, 5
 Butanol, 72

C

Cadaverine, 72
 Cadmium, 151, 159, 172, 179
 liners and, 36
 monitoring, 208
 Calcium, 144, 156, 172, 180
 predicting waste treatability, 86
 Calculation error, 127
 Carbonate-containing minerals, 144
 Carbonates, 144
 Carbon dioxide, 59, 60
 Carbon monoxide, 59
 Carbonyl-containing compounds, 60
 Cation exchange capacity (CEC), 29, 85
 Cations, 185
 CEC, see Cation exchange capacity
 Cell, 9, 18

- Cements, 27, 33
- CFU, see Colony forming units
- Channels, 64
- Chemical analyses, 8, 85—86
- Chemical combination, 3, 66
- Chemical liners, 30
- Chemical nature of odors, 68
- Chemical oxygen demand (COD), 46
- Chemical properties of soil, 79, 204
- Chlorinated hydrocarbons, 79
- Chlorine, 152
- Chloroform, 66
- Chromium, 152, 172, 179
 - attenuation and, 29
 - monitoring, 208
- Chronic microbial toxicity, 91
- Classification
 - liners, 31
 - soils, see also Appendix A, 6—7
- Clays, see also specific types
 - bentonite, 15
 - Davidson, 151
 - hydrogen ion concentration of acid wastes and, 156
 - kaolin-like, 29
 - landfills, 9, 14, 16, 19
 - lattice, 15
 - liners, 30, 51
 - mica-like, 29
 - montmorillonite, 15, 29, 146
 - Nicholson silty, 151
 - predicting waste treatability, 72, 79, 80, 114
 - soil filter-scrubbers, 72
- Climate, 16, 17
- Closure, 191, 211—214
- Cobalt, 152, 159, 162, 172, 179
- COD, see Chemical oxygen demand
- Collection of gases, 64
- Colony forming units (CFU), 87
- Columns, 123, 147—148
 - effluent in
 - predicting waste treatability, 100, 110
 - strong inorganic acids, 152, 158—159
 - strong organic acids, 162
 - strong spent-acid waste, 167, 173, 176, 180
 - flow characteristics
 - strong inorganic acids, 156, 158, 159
 - strong organic acids, 162
 - strong spent-acid waste, 165—166, 173, 176, 180
 - homogeneous, 28
 - influent in, 100, 109
 - kinds of, 106—107
 - packing of soil in, 101—103
 - preparation of soil for, 101
 - soil-, 99—118
 - advantages, 118
 - data collection and processing, 110—112
 - effluent, 110
 - influent, 109
 - limitations, 118
 - packing, 101, 103
 - predicting pollutant movement, 112—118
 - preparation, 101
 - soil selection, 100—102
 - testing equipment, 106—108
 - transport vehicle, 103—106
- Compactability, 14
- Compaction, 31—33
 - equipment and methods for, 34—35
 - stage-, 33
- Compost filters, 71
- Composting, 3, 64
- Concentration, 3
- Conceptual models
 - predicting pollutant movement, 124
 - predicting waste treatability, 116
- Constant, continuous waste loading, 43
- Constituents of pollutants, 185
- Constituents of soil
 - movement of, 158—162, 167—180
 - solubility of, 183
- Contamination
 - degree of, 42
 - rate of, 42, 43
- Controlled-environment pot experiments, 93—94
- Controlled laboratory tests, 80—81
- Convective transfer of gas, 61
- Copper, 151, 159, 162, 173, 179
 - attenuation and, 29
 - monitoring, 208
- Covers
 - control of, 20, 64
 - landfills and, 16—20
 - vegetative, 19
- CPE laminated liners, 51
- Crushed limestone, 15, 27, 36—39
- Cyanides, 72, 208
- Cypress dome process, 55
- Cyprus-Bagdad, copper mine, spent acid wastes, 176—180

D

- Dams, 53
- Davidson clay, 151, 157
- Decomposition gases, 66
- Degree of contamination, 42
- Dehydrogenase activity method, 90—91
- Depth of soil cover, 17
- Detection of odors, 67—68
- Detoxification, 5
- Dilation plating technique, 87—88
- Dilute aqueous inorganic fluids, 104
- Dimethyldisulfide, 66
- Displacement, 124—125
- Duck weed (*Lemna minor*), 55
- Duisberg-Huckingen compost filter, 71
- Dumping, 5
- Dust, 69

E

- Earth filters, 70
- Earth materials, see also specific materials, 64
- EC, see Electrical conductivity
- Effluent
 - analyses of, 148
 - column of, 100, 110
 - strong inorganic acids, 152, 158—159
 - strong organic acids, 162
 - strong spent-acid waste, 167, 173, 176, 180
- Eichhornia crassipes* (water hyacinths), 54
- Electrical conductivity (EC), 46, 79, 130
- Embankment ponds, 53—54
- Emission spectroscopy, 148
- Encapsulations, 25, 50, 213
- Environmental monitoring, 191
- Equations, see also specific equations
 - gas production, 60
 - Lapidus-Amundson, 80, 125—131
 - prediction
 - pollutant movement, 123, 128—131
 - waste treatability, 116—118
 - soil loss, 96
 - user-oriented, 123
 - wind erosion, 96—97
- Erodibility, 17
- Erosion
 - control of, 20
 - soil, 96—98, 208—211
 - wind, 96—97
- Error function (EF), 80
 - model of, 131—136, 138—140
- Error of calculations, 127
- Ethylene, 72
- Excavated ponds, 53, 54

F

- Failure-stabilization of soil, 185—187
- Fertility, 17
- Field tests, 29, 80—81, 90, 94—95
- Filter-scrubbers, 69—72
- Flow characteristics of columns
 - strong inorganic acids, 156, 158, 159, 162
 - strong spent-acid waste, 165—166, 173, 176, 180
- Free iron oxides, 85
- Freezing, 48
- Freshwater ponds, 52—55
- Fungi, 87

G

- Gases, see also specific gases, 59
 - absorption of, 64
 - collection of, 64
 - control of, 18—20, 59—67
 - decomposition, 66
 - diffusion of, 61
 - exchange rate for, 17
 - flow of through soil, 18
 - mass transfer of, 61

- monitoring of, 66—67
- movement of through soil, 61—63
- origin and nature of, 59—61
- permeability of, 63, 71
- production equations for, 60
- reduction of in production, 63

- Geohydrology, 204—208
- Glucose agar, 87
- Grasses, for cover, 22
- Grasses for revegetation, 23—24

H

- Hazardous waste land treatment, 77—78
 - site selection, 196, 197, 200, 201
- Hazardous wastes, see also Pollutants
 - evaluation project, 90
 - industrial, 30
 - land treatment, see Hazardous waste land treatment
- Heavy metals, see also specific metals, 148, 159, 162, 163, 172
 - mobility of, 29
 - predicting waste treatability, 78, 79, 115
 - transport rates of, 78
- Homogeneity, 14
- Homogeneous columns, 28
- HWLT, see Hazardous waste land treatment
- Hydrocarbons, 79
 - breakdown of, 72
- Hydrogen, 59
- Hydrogen ion concentration, see pH
- Hydrogen sulfide, 59, 66
- Hydrology, 204—208
- Hydroseeding, 21
- Hydrous oxides of iron, 41—42, 208
- Hypalon, 51

I

- Illite, 15
- Impermeable synthetic liners, 51
- Impoundments, 50—51
- Incineration, 3
- Influent
 - application of to soil, 109
 - column of, 100
- Inorganic acids, see also specific acids, 152—162
 - nitric acid, 156—158, 165—176, 184
 - phosphoric acid, 158—160, 180, 184
 - sulfuric acid, 159, 161—162, 176, 184
- Inorganic fluids, 104
- Iron, 144, 151, 167, 179
 - hydrous oxides of, 41—42, 208
 - liners and, 36
 - monitoring, 208
 - oxides of, 41—42, 85, 208
 - predicting waste treatability, 79, 86
- Iron chloride-aluminum chloride solution, 151—152

K

Kaolinite, 15
Kaolin-like clay, 29

L

Laboratory Toxicity Reduction (TR), 89
Land disposal types, 193
Landfills, see Sanitary landfills
Landscape, 20, 21, 203—204
Land treatment utilization, 214
Lapidus-Amundson model, 80, 125—131
Lattice clays, 15
LC, see Limiting constituents
Leachates, 27, 147, 155—156
 control of, 20
 gas control and, 66
 landfill and, 14, 15, 104, 105
 liners and, 44—50
 predicting waste treatability and, 79, 80, 86
 regression analysis and, 130, 134—136
 relationships of, 39—40
Lead, 152, 173, 179
 attenuation and, 29
 monitoring, 208
Legumes, for cover, 22
Legumes for revegetation, 23—24
Lemna minor (duck weed), 55
Lesser fairy moss (*Azolla caroliniana*), 55
Lift, 9
Lime, 183
Limestone, 64, 72
 crushed, 15, 27, 36—39
 liners of, 36—41
 particle size of, 40
 quality of, 40—41
 thickness of, 41
Limiting constituents (LC), 94
Liners, see also specific topics, 27
 absorptive capacity of, 42
 burials and, 42—50
 chemical, 30
 classification of, 31
 concepts of, 30—31
 freshwater ponds and, 52—55
 impermeable synthetic, 51
 impoundments, 50—51
 landfills, 13—16, 30—42
 leachate and, 44—50
 limestone, 36—41
 permeability of, 42
 ponds, 52—55
 sanitary landfills and, 13—16
 surface impoundments and, 50—51
 synthetic, 51
Loading, 3
 constant, continuous waste, 43
 single unit, 43

Loams, 9, 27, 30, 151
Loamy soils, 30
Lysimeters, 99

M

Magnesium, 144, 152, 162, 172, 180
Manganese, 151, 170, 179
 attenuation and, 29
 predicting waste treatability, 79, 86
Marshlands, 55
Mass transfer of gas, 61
Mathematical models
 predicting pollutant movement, 123—125
 predicting waste treatability, 116
Mechanical analysis, 86
Mercaptan, 72
Mercury, 29, 208
Metals, see also specific metals
 attenuation of in soils, 79
 heavy, see Heavy metals
 trace, see Trace metals
Methane, 59, 60, 66
Methylmercaptan, 66
Mica-like clay, 29
Microbial aerosols, 68—69
Microbial population and biodegradation, 86—88
Microbial toxicity
 acute, 89—91
 chronic, 91
Microorganisms and aerosols, 68
Migration rates of pollutants, 3, 204
Minerals, see also specific minerals
 carbonate-containing, 144
 excess of, 93
Miscible displacement, 124—125
Mobility of heavy metals, 29
Models, see also specific types, 123
 conceptual, 116, 124
 defined, 116
 error function, 131—136
 Lapidus-Amundson, 80, 125—131
 mathematical, 116, 123—125
 physical, 116, 124
 prediction, 116—118, 123, 128—131
 simulation, 116
Mohave clay loam, see also Reference soils, 157, 158, 176
Molybdenum, 172
Monitoring, 201—211
 environment, 191
 gases, 66—67
 geohydrology, 204—209
 hydrology, 204—209
 landscape, 203—204
 odor, 68
 soil erosion, 208, 210—211
 soil properties, 204
 topography, 203—204
 waste properties, 203
 wells, 205
Montmorillonite clays, 15, 29, 146

Movement

- gas through soil, 61—63
- odors, 67—68
- soil constituents, 158—162, 167—180

Mulching, 22, 25

Multiple regression analysis, 128—129

Municipal solid wastes (MSW), see also Columns.

- Leachates, Sanitary landfills
 - characteristics, 44
 - common ions in, 156
 - effects on liners, 44—50
 - heavy metals in, 152
 - waste gases in, 59—61, 66—67

Mutagenicity, 91

MSW, see Municipal solid wastes

N

Natural field tests, 80—81

Natural soil constituents, 182

Neoprene, 51

Nicholson silty clay, see also Reference soils, 114, 157, 151

Nickel, 151, 159, 162, 172, 179

Nitric acid, 156—158, 165—176, 184

Nitrogen, 59

- compounds containing, 60

Nut hulls, 15

Nutrient agar, 87

O

Odors, 59

- acceptability of, 68
- chemical nature of, 60, 68
- control of, 67—68
- detection and movement of, 67—68
- monitoring of, 68
- origin and nature of, 67

Oils, see also specific oils

- petroleum, 79
- transport rates of, 78

Open burning, 5

Open dumping, 5

Organic acids, see also specific acids

- effects of on soil, 162—164

Organic compounds, volatile, 60

Organic fluids, 104—105

Organic solvents, 79, 80, 106, 208

- transport rates of, 78

Organohalogens, 72

Organonitrogen compounds, 72

Organosulfur gases, 72

Oxic equipment, 109

Oxidation, 70

Oxidation-reduction reactions, 45, 184

Oxidative ponds, 52

Oxidizing agents, 105—106

P

Packing of soil in columns, 101—103

Parameter estimation, 127

Particle density of soil, 86

Particle size of limestone, 40

PCP, see Pentachlorophenol

Pentachlorophenol (PCP), 72, 79

Permeability, 95

- gas, 71
- liners, 32, 33, 42
- soil, 42, 80, 164, 183

Petroleum oils, 79

pH, 148, 182

- burial liners and, 45
- dilute acids, 151—152
- effect on soils, 143—190
- predicting pollutant movement, 130
- predicting waste treatability, 79
- strong inorganic acids, 158, 159, 162
- strong spent-acid waste, 167, 173, 176, 180

Phenols, 79

Phosphates, 180, 185

Phosphoric acid, 159, 180—181, 184

Physical analyses, 8, 86

Physical models

- predicting pollutant movement, 124
- predicting waste treatability, 116

Physical properties of soil

- predicting waste treatability, 79
- monitoring and, 204
- site selection and, 194—201

Phytotoxicity, 91—94

Pilot experiments, 80—81

Piping, 64

Plant growth decrement, 93

Plastic, 51

Podzolization process, 144

Pollutants, see also Leachates, Liners, specific types

- attenuation of, 42—44
- constituents of, 185
- movement prediction for, 112—118, 123
- ranking of by soil interactions, 124

Ponds

- aquaculture, 54—55
- biological treatment, 52
- embankment, 53—54
- excavated, 53, 54
- freshwater, 52—55
- liners for, 52—55
- oxidative, 52
- sediment collection, 53

Pore size distribution, 86

Pore volume, 86

Porosity of soil, 86

Postmonitoring, 203

Potassium, 152, 162, 170, 180

- predicting waste treatability, 86

Potato-glucose agar, 87

Prediction, models for

- pollutant movement, 112—118, 123

waste treatability, 123, 128—131
 Premonitoring, 202—203
 Productivity, 17
 Profile analyses of soil, 8
 Public relations, 21
 Putrescine, 72
 Pyrolysis, 3

R

Radon gas, 66
 Reagent grade, 146
 Recycling, 3
 Reduction
 gas in production, 63
 toxicity, 89, 90
 Reduction-oxidation reactions, 45, 184
 Reference soils, see also Columns, 101, 103
 Regression analysis, definition and uses, 128—129
 Relative mobility of heavy metals, 29
 Respirometry, 88
 Revegetation, 20—21
 grasses used for, 23—24
 legumes used for, 23—24
 Root mat technique, 93
 Rose bengal-streptomycin agar, 87

S

Salt-expanded soil, 33
 Salts, 183
 total soluble (TDS), 151
 Sampling of soil, 81—85
 Sand, 79
 Sandy loams, 151
 Sandy soils, 9, 16, 72, 114
 Sanitary landfills (SLF), 3—21, 214
 covers for, 16—20
 development, 4—5
 limitations, 5
 liners for, 13—16, 42—50
 site selection for, 5—9
 soil, 9—21, 23—24
 covers, 16—20
 liners, 13—16, 42—50
 revegetation, 20—21, 23—24
 Screening tests, 80—81
 Sealants, 33—36
 Sediment collection ponds, 53
 Seed germination method, 91—92
 Seeding, 21
 establishment method for, 92—93
 Selection of soil, 100—101
 Selenium, 29, 208
 Silicon, 169, 179
 Simulation mathematical models, 116
 Single unit load, 43
 Site closure, 191, 211—214
 Site selection, 27, 191—201

 for sanitary landfills, 5—9
 SLF, see Sanitary landfills
 Sodium, 152, 162, 170, 180
 predicting waste treatability, 86
 Soil cements, 27, 33
 Soil columns, see Columns
 Soil extract, 87
 Soil loss equation, 96
 Soil sampling, 81—85
 Soil sealants, 33—36
 Soil selection, 100—101
 Soil-waste reactions, 3
 Soluble ions, 46
 Solute profile, 131—133
 Solvents, see also specific solvents, 66
 organic, see Organic solvents
 products of, 79
 Sorption, 70
 Spectroscopy, 148
 Spent-acid wastes, 146—147, 164—181, 184
 nitric acid, 165—167, 169—176
 phosphoric acid, 180—181
 sulfuric acid, 176—180
Spirodela oligarhiza, 55
 Stabilization-failure of soil, 185—187
 Stage-compaction, 33
 Standard X-ray, 86
 Stanford-DeMent test, 92
 Statistical analyses, 112
 Streptomycin agar, 87
 Strong inorganic acids, see also specific acids,
 152—162
 nitric acid, 156—158
 phosphoric acid, 159, 161—162
 sulfuric acid, 158—160
 Strong organic acids, see also specific acids, 162—
 164
 Strong spent-acid waste, effects on soil, see also
 Spent-acid wastes, 164—181
 Subsurface disposals, 85
 Sulfur-containing compounds, 60
 Sulfuric acid, 69, 151, 158—160, 176—180, 184
 Surface disposals, 85
 Surface impoundments, 50—51
 Sylvania, spent acid wastes, 165—167, 169—173
 Synthetic liners, 51

T

TCE, 79
 TDS, see Total dissolved solids
 Tests, see also specific types
 controlled laboratory, 80—81
 field, 29, 80—81
 screening, 80—81
 Stanford-DeMent, 92
 Texture of soils, 182—183
 landfills and, 9, 13, 14, 17, 19
 soil filter-scrubbers and, 72
 Thickness of limestone, 41

Thin-layer chromatography (TLC), 99
 Titanium, 159, 170
 TLC, see Thin-layer chromatography
 TOC, see Total organic carbon
 Toluene, 79, 80
 Topography, 203
 Total dissolved solids (TDS), 79
 Total organic carbon (TOC), 146, 183
 burial liners and, 46
 predicting pollutant movement, 128
 predicting waste treatability, 86, 90
 soil filter-scrubbers and, 70
 Total soluble salts, 151
 Toxicity
 acute microbial, 89—91
 chronic microbial, 91
 level of, 81
 reduction of, 89, 90
 TPF, see Triphenylformozan
 Trace metals, 163, 206
 Transport rates, 78
 Transport system, 103—106, 183—185
 Trenches, 21—25, 50
 Trichloroethane, 66
 Trichloroethylene, 80
 Triphenylformozan (TPF), 90
 2,3,5-Triphenyltetrazolium chloride (TTC), 90
 TTC, see 2,3,5-Triphenyltetrazolium
 Types of soil, see also specific types, 9—21
 covers, 8, 10—12, 16—20
 liners, 13—16
 revegetation, 20—21, 23—24

U

Uranium mill tailings, 66
 User-oriented predictive equations, 123

V

Vanadium, 29

Vegetation
 as cover, 19
 establishment of, 17
 functions of, 20
 Velocity estimation, 128
 Vents, 64
 Vertical movement of polluting metals, 127—128
 Vertical mulching, 22, 25
 Volatile odorous organic compounds, 60
 Volatilization, 95—96

W

Waste burial, see Burials
 Waste characteristics, 44, 203
 Water, see also Wells
 effect of on soils, 148—151
 groundwater, 27, 206, 212
 infiltration and penetration of, 17
 runoff of, 97—98
 Water-holding capacity, 17
 Water hyacinths (*Eichhornia crassipes*), 54
 Wells
 injections, 213
 monitoring, 205
 Wind erosion equations, 96—97
 Wolverine, spent acid wastes, 173—176

X

X-ray, 86, 146
 Xylene, 79, 80

Z

Zinc, 151, 159, 162, 173, 179
 monitoring and, 208